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Summary

We performed Monte Carlo calculations of the neutron and gamma ray spectra and neutron and gamma dose rates outside the shielding of the UF_6 mass flowmeter. TheUF_6 mass flowmeter and the UF_6 mass flowmeter are the two main components of the Blend Down Monitoring System (BDMS) equipment. The BDMS equipment is designed to continuously monitor the UF_6 enrichment and mass flow rates in processing pipes at uranium facilities. The UF_6 mass flowmeter incorporates four ^{252}Cf neutron sources, surrounded by a polyethylene shielding block. The uranium fission products generated by the ^{252}Cf neutrons are detected down the pipe, thus confirming the UF_6 mass flow rate. The dose calculations used both U.S. and Russian gamma and neutron fluence-to-dose conversion coefficients. The purpose of these calculations was to facilitate proper interpretation of the neutron dose rate measurements from rem meters (e.g., rem balls) outside of BDMS shielding. An accurate determination of the dose rate is of particular interest in that it enables dose rates to be compared with the applicable regulatory limit. The calculations show that neutrons outside of BDMS shielding are significantly reduced in energy, i.e., the spectrum is shifted (i.e., moderated) towards lower energies and contains significantly larger amount of neutrons in the energy range below 100 keV. Results of the calculations indicate that neutron dose rate measurements taken outside of BDMS shielding are overestimated by 25% to 55%, depending on the location around BDMS, when using either Russian or U.S. dose conversion coefficients. For an accurate neutron dose rate evaluation, application of an appropriate correction factor to the neutron dose rate measurements is necessary.

Background

Gamma exposure survey instruments generally provide readings that are directly related to the gamma dose, because the dose conversion factors for gamma and X-rays are considered to be independent of gamma energy. On the other hand, the radiation dose (i.e., dose equivalent) from neutron radiation depends on several factors, most notably neutron energy and relative biological effectiveness as function of neutron energy (i.e., quality factor, Q). Therefore, the knowledge of the neutron energy distribution is essential in neutron dosimetry. For any given energy, the dose from neutrons $\mathbf{D_e}$ is proportional to the number of neutrons **N** and the quality factor **Q**.

$$\mathbf{D_e \sim N \cdot Q}$$

The quality factor Q is strongly dependent on the neutron energy. Therefore, the same amount of neutron radiation delivers a different amount of dose depending on its energy and consequently has a different health effect to the human body. U.S. and Russian safety regulations provide tables with Q values or the associated neutron-fluence-to-dose conversion coefficients for different energy intervals. The current quality factors used in the U.S. and Russia are presented in Table 1 and in Figure 1.

Table 1. Neutron quality factors.[a]

Neutron Energy (MeV	U.S. 10CFR835 (1998) and NCRP 38 (1985)	Russian NRB-99
2.5×10^{-8} thermal	2	5
1×10^{-7}	2	
1×10^{-6}	2	
1×10^{-5}	2	
1×10^{-4}	2	
1×10^{-3} (1 keV)	2	
1×10^{-2} (10 keV)	2.5	10
1×10^{-1} (100 keV)	7.5	
5×10^{-1} (500 keV)	11	20
1	11	
2.5	9	
5	8	10
7	7	
10	6.5	
14	7.5	
20	8	
40	7	5
60	5.5	
100	4	

[a] U.S. Q factors are defined as the maximum value in a 30 cm dosimetry phantom. Russian NRB-99 Q factors are defined for neutron "radiation incident on a human body."

Regarding the value of quality factors for neutrons, the International Commission on Radiation Protection (ICRP) issued the following statement from its meeting in Paris in March 1985 (ICRP, 1985b):

> "The information now available on the relative biological effectiveness (RBE) for neutrons for a variety of cellular effects in vitro, and for life shortening in the mouse, is being reviewed by the Commission. The implications of this information will be considered as part of a larger review of recommendations to be undertaken by the Commission over the next four or so years. Meanwhile, in the case of neutrons, the Commission recommends an increase in Q by a factor of 2. The permitted approximation for Q for fast neutrons thus changes from 10 to 20. This changes relate only to neutrons, and no other changes are recommended at this time."

The change in Q factors for neutrons is not introduced into all national procedures, which may explain the difference between U.S. and Russian regulatory Q factors.

For example, if two individuals are exposed to the same amount of monoenergetic neutrons but with different energies E_1 and E_2, and the respective quality factor for energy E_2 is twice as large as for E_1 (i.e. $Q_2 = 2.Q_1$), then the radiation dose D_2 from neutrons with energy E_2 will be two times greater then the dose D_1 from neutrons with energy E_1 (i.e. $D_2 = 2.D_1$). If we have non-monoenergetic neutrons with some spectral distribution, the dose from these neutrons is determined by integrating the product of the number of the neutrons in each energy interval and the corresponding quality factor for that energy.

$$\mathbf{D \sim \int N(e) \cdot Q(e) \cdot de}$$

Therefore, to determine accurately the radiation dose from neutrons with a wide spectrum, knowledge of the neutron spectrum distribution **N(e)** is essential. No consensus currently exists on the appropriate choice for the value of the quality factor for neutrons. A variety of factors have been recommended by national, international, and regulatory bodies. These factors vary due to differences in the choice of phantom geometry, depth at which the dose equivalent is to be determined, and the assessment of the relative biological risk of neutrons to photons. The latest American National Standard Institute (ANSI) standard N13.52, "Personnel Neutron Dosimeters," [1] does not adopt or preclude the use of any of the conventions listed above. More information and discussion is provided in Appendix 1.

Dose Estimation From Neutrons Moderated by BDMS Shielding

BDMS equipment is comprised of two separate units: a UF_6 mass flowmeter and an enrichment monitor. The UF_6 mass flowmeter consists of a source module, a detector module, and the accompanying support structure (Figure 2). The BDMS flow monitor is designed to continuously monitor the mass flow rates in processing pipes at uranium facilities from the amount of uranium fissions induced by ^{252}Cf neutrons [2–11].

BDMS shielding reduces (i.e., moderates) the energy of neutrons from ^{252}Cf sources. A neutron-absorbing shutter moves back and forth in front of the ^{252}Cf sources, thus changing their energy and intensity. The dose from neutrons with a moderated spectrum is expected to be less than the dose from a bare ^{252}Cf source. This is the case because the quality factor for the average neutron energy of a bare ^{252}Cf source (E_{av} = 2.3 MeV) is 4 to 5 times higher then the quality factor for neutron energies below 1 keV (see Figure 1 and Table 1). Therefore, for accurate determination of the dose from BDMS-moderated neutrons, it is necessary to know how many neutrons have been moderated and how much their energy was reduced On the other hand, in a variety of applications it has been reported that the use of a 10" polyethylene sphere dose meter (i.e., rem ball) leads to a maximum dose overestimation of 65% [12].

One can measure or calculate the BDMS neutron spectrum; however, the measurement of the neutron spectrum is a rather complex and time-consuming task. There is no single detector or technique that can be applied for the entire energy spectrum. Measurement therefore requires the calibration of several types of detectors with suitable sources in many overlapping energy intervals. Few laboratories have the complete set of neutron detectors, the neutron spectra unfolding methodologies, and calibration sources to perform an accurate measurement of a wide neutron spectrum. On the other hand, calculation of the spectrum even in relatively complex geometries can be done accurately. This approach takes less time and effort and overall is safer and more cost-effective.

Calculation of Moderated Neutron and Gamma Spectra Outside of BDMS Shielding

LLNL ran a series of Monte Carlo calculations to estimate the neutron and photon spectra and the associated doses outside the BDMS shielding. The BDMS mass flow monitor contains four ^{252}Cf neutron sources (~ 3 μg each) with a total strength of approximately 12 μg located in the source module at 2 cm from the flow pipe. The flow monitor's source module is a cylindrical drum of polyethylene mounted on a steel pipe through which UF_6 gas flows. The inside and outside radii of the pipe are 5.0 and 5.4 cm. The geometry of the source module is shown in Figures 2, 3 and 4. The ends of the drum are covered with 1.27 cm of ^{6}Li-epoxy, while radially the drum is wrapped by 0.95 cm of ^{6}Li-silicone. Figure 3 is a cross-sectional view along the cylinder radius just off the vertical midplane showing the locations of six nylon rods and four Cf sources. The components are held together by six nylon rods two of which are shown in Figure 4, which represents a lateral view of the shielding assembly along the center of the UF_6 gas pipe. The inside radius of the polyethylene moderator is 7.94 cm, and the outside radius of the source module is 19.05 cm. The thickness of the source module is 22.86 cm. The four ^{252}Cf neutron sources are located on the vertical midplane and are radially 9.525 cm from the center of the pipe and azimutally 90 degrees apart.

As in the earlier calculations [12], the COG code [31] was used with neutron and gamma data derived from ENDL and EPDL libraries and a ^{252}Cf source model based on the IAEA standard of ^{252}Cf [14]. The detector response function was assumed to be independent of the neutron and gamma energies. The neutron and gamma spectra were determined at different locations on the surface and one meter away from the BDMS shielding (Figure 5) for two situations: with the source shutter assembly 1). in the open position and 2). in the closed position.

Calculated Neutron Spectra Outside of BDMS Shielding

Graphs of the neutron spectra at different locations on and around the BDMS shielding are provided in Figures 6–11 for the open shutter position and in Figures 12–17 for the closed shutter position. On these graphs, the left-hand side ordinate scale applies to the spectral distribution of neutrons arriving at a particular location (e.g. 401, ...406). The spectra are normalized to one neutron (arriving at a particular location) per cm^2. The neutron spectra for open and closed shutter positions are quite similar with the exception of the region below 0.4 eV. As expected, the neutron-absorbing shutter reduces the thermal neutron contribution two to five times at different dose measurement locations.

The unmoderated ^{252}Cf neutron spectrum was modeled after the IAEA reference ^{252}Cf source of 1 μg [14] 1 meter from the source. A graph of the calculated neutron spectrum in air 1 meter from a bare ^{252}Cf source, normalized to one neutron per cm^2 per unit energy, is provided in Figure 18.

It is apparent from the graphs that the BDMS-moderated neutron spectra have a lower contribution of high energy neutrons in the range 0.1–5 MeV and a significantly higher contribution of low energy neutrons below 0.1 MeV than the neutron spectra from a bare ^{252}Cf source in air. The increase of the BDMS-moderated neutrons in the energy region below 1 keV is more then four orders of magnitude higher compared with the neutron spectral distribution of a bare Cf source. Figures 19–30 provide a visual representation of the neutron spectra moderation, i.e., shift towards the lower energies, as a result of the BDMS shielding. Figures 19–24 present the cumulative integrals of the normalized BDMS neutron spectra per cm^2 for open shutter position, and Figures 25–30 present the same spectra for the closed shutter position. The cumulative integral of the normalized neutron spectra of a bare ^{252}Cf source is provided in Figures 19–30 for comparison with the curves from moderated neutrons.

Calculated Gamma Spectra Outside of BDMS Shielding
Graphs of the gamma spectra at different locations on and around the BDMS shielding are provided in Figures 31-36 for the open shutter position and in Figures 37–42 for the closed shutter position. On these graphs, the left-hand side ordinate scale applies to the spectral distribution of gammas arriving at a particular location (e.g. 401, ..., 406). The spectra are normalized to one gamma arriving at a particular location per one cm^2. The gamma spectra are almost identical for all BDMS locations and have insignificantly higher contribution in the upper energy spectrum (5-7.5 MeV) for the open shutter cases. There are noticeably fewer gammas in the upper end of the spectrum (5–7.5 MeV) from a bare ^{252}Cf source (Figure 43) than emanating gammas outside the BDMS shielding. Figure 44 provides a visual presentation of any shift of the gamma spectra as a result of interaction with the shielding for location 401 and for the case of an open shutter. Figure 44 is analogous to Figures 19–30. However, graphs for the case of a closed shutter and various locations are not presented because there is no significant shift in the gamma spectra between a bare Cf source and a moderated one. In addition, the quality factor (i.e., relative biological effectiveness) for gamma radiation is independent of energy.

Calculation and Evaluation of the Equivalent Neutron and Gamma Dose Rates Outside of BDMS Shielding

The equivalent neutron and gamma dose rates were estimated using the calculated neutron and gamma spectra, published U.S. and Russian quality factors, and the associated neutron fluence-to-dose and gamma conversion coefficients. A detector response function independent of the energy was used. The data for the quality factors were derived from ANSI standards ANS 6.1.1–1977 [15] and ANS 6.1.1–1991 [16] and NRB-99 (a Russian radiation safety regulatory document) [17]. NRB-99 provides tables of the neutron fluence-to-dose conversion coefficients for two types of neutron radiation (see Table 2). The first type is an isotropic neutron field, in which neutrons strike the body uniformly from every direction (IRF column in Table 2); the second is a parallel neutron field, in which neutrons strikes the body in parallel beam in front-to-back direction (F-B column in Table 2). The U.S. neutron fluence-to-dose conversion coefficients, derived from ANSI standards [15] and [16], are interpolated for the same energy intervals as the Russian ones and are presented in Table 2 for comparison. Additional information on the controversy surrounding the best choice for the quality factor and the neutron fluence-to-dose conversion coefficients is provided in Appendix 1.

Table 2. U.S. and Russian neutron fluence-to-dose conversion coefficients.

Neutron energy	Effective whole body dose per unit fluence (1E-10 rem-cm^2)			
[MeV]	U.S. Dose '77	U.S. Dose '91	Russian IRF[a]	Russian F-B
Thermal	10.2	2.85	3.30	7.60
0.0000001	10.2	2.85	4.13	9.95
0.000001	10.2	2.85	5.63	13.8
0.00001	10.2	2.85	6.44	15.1
0.0001	10.3	2.87	6.45	14.6
0.001	11.1	3.03	6.04	14.2
0.01	18.9	4.62	7.70	18.3
0.02	27.6	6.40	10.2	23.8
0.05	53.7	11.7	17.3	38.5
0.1	97.3	20.6	27.2	59.8
0.2	159	38.1	42.4	99.0
0.5	257	84.8	75.0	188
1.0	360	141	116	282
1.2	362	159	130	310
2.0	352	214	178	383
3.0	368	260	220	432
4.0	404	295	250	458
5.0	432	323	272	474
6.0	420	345	282	483
7.0	409	365	290	490
8.0	408	383	297	494
10.0	413	414	309	499
14.0	577	467	333	496
20.0	757	539	343	480

[a] IRF represents the isotropic (4π) radiation field; F-B, parallel-beam irradiation with front-to-back geometry.

Equivalent Neutron Dose Rates Outside of BDMS Shielding

Graphs of the energy distribution of the equivalent neutron dose rates at different locations on and around BDMS are plotted on the same charts, together with the neutron spectra for open (Figures 6–11) and closed (Figures 12–17) shutter positions. The dose ordinate scale is on the right hand-side of the chart and is given in units of rem per one neutron (arriving at the particular location) per cm^2. The dose distributions are presented on each chart for the two U.S. and two Russian neutron fluence-to-dose conversion factors. Table 2 provides the latest published Russian neutron fluence-to-dose conversion coefficients [17].

The neutron dose rates at any location are determined by the contribution of the neutrons at each of the energies in the spectrum. Therefore, to obtain the total neutron dose rate, it is necessary to integrate the partial neutron dose rates over the entire spectrum. A summary of the integrated neutron dose rates at 1 meter away from both a bare ^{252}Cf source and a ^{252}Cf source moderated by the BDMS shielding neutrons at different locations on and around the BDMS shielding is provided in Table 3. The dose rates are normalized to one neutron arriving at the particular location per one second.

Table 3. Neutron dose summary.

Location	Int. Spectrum [neutrons/cm^2]	Int. Dose-U.S.'77 [rem/neutron]	Int. Dose-U.S.'91 [rem/neutron]	Int. IRF - Russ. [rem/neutron]	Int. F-B - Russ. [rem/neutron]
Calibration (@ 1 m)					
IAEA reference Cf-252 source	1.9370E+01	3.3984E-08	1.9587E-08	1.6403E-08	3.4162E-08
BDMS spectrum (shutter open)					
Detector position 401	3.1203E+02	1.7111E-08	8.7058E-09	7.3611E-09	1.5821E-08
Detector position 402	2.3799E+02	1.9266E-08	9.9260E-09	8.3972E-09	1.7957E-08
Detector position 403	1.5093E+01	2.4804E-08	1.5067E-08	1.2566E-08	2.5060E-08
Detector position 404	6.1280E+01	2.1940E-08	1.1682E-08	9.8446E-09	2.0861E-08
Detector position 405	4.7936E+00	1.7642E-08	8.8722E-09	7.5220E-09	1.6164E-08
Detector position 406	1.7570E+00	2.3436E-08	1.4243E-08	1.1871E-08	2.3637E-08
BDMS spectrum (shutter closed)					
Detector position 401	2.5519E+02	1.9198E-08	9.8459E-09	8.3321E-09	1.7851E-08
Detector position 402	2.5181E+02	1.8335E-08	9.3508E-09	7.9143E-09	1.6984E-08
Detector position 403	1.4642E+01	2.4806E-08	1.5092E-08	1.2582E-08	2.5084E-08
Detector position 404	6.4097E+01	2.1608E-08	1.1434E-08	9.6486E-09	2.0473E-08
Detector position 405	4.9932E+00	1.7060E-08	8.5443E-09	7.2406E-09	1.5593E-08
Detector position 406	1.6437E+00	2.4344E-08	1.4807E-08	1.2346E-08	2.4580E-08

The integrated neutron dose rates vary approximately 10% for the open and closed source shutter positions. The actual difference depends on the particular location where the dose rate is evaluated because the source–detector geometry and the shutter position are not symmetrical for all locations. As can be seen from the summary in Table 3, the integral dose rates calculated with both U.S. and Russian dose conversion coefficients are 25% to 55% smaller than the dose rates from a bare ^{252}Cf source. This difference depends on the particular location around the BDMS. For location 406 (one meter away from the BDMS shielding), the overestimation of the dose rate from BDMS moderated neutrons over a dose rate from a bare ^{252}Cf source is 25% to 40%, depending on the particular fluence-to-dose conversion coefficients used. Therefore, we can conservatively assume that for locations one meter away from BDMS shielding, the overestimation is at least 25% compared to measurements made with a dose meter calibrated with a bare ^{252}Cf source.

Gamma Dose Rates Outside of BDMS Shielding

Graphs of the energy distribution of the gamma dose rates at different locations on and around BDMS are plotted on the same charts together, with the gamma spectra for open (Figures 31–36) and closed (Figures 37–42) shutter positions. The dose ordinate scale is on the right hand-side of the chart and is given in units of rem per one gamma (arriving at the particular location) per cm^2. The dose distributions are presented on each chart for the U.S. and Russian gamma conversion factors. Table 4 provides the latest published Russian gamma fluence-to-dose conversion coefficients [17] and the U.S coefficients [15, 16] interpolated for the same energy intervals.

Table 4. U.S. and Russian gamma fluence-to-dose conversion coefficients.

Photon energy	Effective whole body dose per unit fluence (1E-10 rem-cm^2)			
[MeV]	U.S. Dose '77	U.S. Dose '91	Russian IRF[a]	Russian F-B
0.01	3.82	0.185	0.0201	0.0485
0.02	3.73	0.206	0.0384	0.125
0.02	3.65	0.227	0.0608	0.205
0.03	3.49	0.270	0.103	0.300
0.04	3.32	0.312	0.140	0.338
0.05	3.16	0.354	0.165	0.357
0.06	2.99	0.397	0.186	0.378
0.08	2.66	0.481	0.230	0.440
0.1	2.33	0.566	0.278	0.517
0.2	1.51	0.778	0.419	0.752
0.2	1.40	1.02	0.581	1.00
0.3	2.10	1.56	0.916	1.51
0.4	2.69	2.06	1.26	2.00
0.5	3.24	2.54	1.61	2.47
0.6	3.76	2.99	1.94	2.91
0.8	4.67	3.82	2.59	3.73
1.0	5.49	4.57	3.21	4.48
2.0	8.91	7.69	5.84	7.49
4.0	14.0	12.5	9.97	12.0
6.0	18.2	16.7	13.6	16.0
8.0	22.3	20.7	17.3	19.9
10.0	26.4	24.8	20.8	23.8

[a] IRF represents the isotropic (4π) radiation field; F-B, parallel-beam irradiation with front-to-back geometry.

Calculation of Total Equivalent Dose Rates Outside of BDMS Shielding

Neutron radiation is always accompanied by gamma radiation from the source and from activation or induced neutron reactions. Therefore, the total dose rate around BDMS is the sum of the neutron and gamma dose rates. Dose rates were calculated from a neutron source consisting of four 3 μg ^{252}Cf sources located in the source module of the BDMS UF_6 mass flow monitor as described in [2–11] and using a detector response function independent of the energy. The calculated neutron, gamma, and total equivalent dose rates are presented in Table 5 in units of mrem/hr. The data for the IAEA reference ^{252}Cf source (1 μg) are presented in Table 5 for comparison.

Table 5. Neutron, gamma, and total radiation dose rates at different locations around BDMS.

Location	Int. Spectrum [#/cm^2/sec]	Dose Rate [mrem/hr] U.S. '77	Dose Rate [mrem/hr] U.S. '91	Dose Rate [mrem/hr] Russian -IRF	Dose Rate [mrem/hr] Russian F-B
Neutron					
IAEA Cf-252 reference	1.9370E+01	2.3697E+00	1.3658E+00	1.1438E+00	2.3822E+00
BDMS (shutter open)					
Location 401	1.5602E+02	9.6103E+00	4.8897E+00	4.1344E+00	8.8859E+00
Location 402	1.1900E+02	8.2532E+00	4.2522E+00	3.5973E+00	7.6927E+00
Location 403	7.5467E+00	6.7388E-01	4.0934E-01	3.4139E-01	6.8083E-01
Location 404	3.0640E+01	2.4201E+00	1.2885E+00	1.0859E+00	2.3011E+00
Location 405	2.3968E+00	1.5223E-01	7.6554E-02	6.4903E-02	1.3947E-01
Location 406	8.7851E-01	7.4119E-02	4.5045E-02	3.7543E-02	7.4753E-02
BDMS (shutter closed)					
Location 401	1.2759E+02	8.8181E+00	4.5225E+00	3.8272E+00	8.1995E+00
Location 402	1.2590E+02	8.3103E+00	4.2383E+00	3.5872E+00	7.6979E+00
Location 403	7.3212E+00	6.5378E-01	3.9777E-01	3.3161E-01	6.6111E-01
Location 404	3.2048E+01	2.4930E+00	1.3192E+00	1.1132E+00	2.3620E+00
Location 405	2.4966E+00	1.5333E-01	7.6793E-02	6.5076E-02	1.4015E-01
Location 406	8.2185E-01	7.2027E-02	4.3808E-02	3.6527E-02	7.2724E-02
Gamma					
IAEA Cf-252 reference	1.0574E+02	1.6023E-01	1.3129E-01	9.0397E-02	1.2783E-01
BDMS (shutter open)					
Location 401	3.9976E+02	6.7301E-01	5.5947E-01	4.0195E-01	5.4276E-01
Location 402	4.7276E+02	7.6938E-01	6.3692E-01	4.5415E-01	6.1822E-01
Location 403	1.9717E+02	3.5338E-01	2.9382E-01	2.1267E-01	2.8494E-01
Location 404	1.2625E+02	2.3324E-01	1.9480E-01	1.4012E-01	1.8920E-01
Location 405	1.7583E+01	2.9003E-02	2.3994E-02	1.7189E-02	2.3267E-02
Location 406	2.0501E+01	3.9293E-02	3.2905E-02	2.3984E-02	3.1922E-02
BDMS (shutter closed)					
Location 401	3.7003E+02	5.7957E-01	4.7666E-01	3.3676E-01	4.6304E-01
Location 402	4.1389E+02	6.3163E-01	5.1841E-01	3.6495E-01	5.0362E-01
Location 403	1.8005E+02	3.1090E-01	2.5713E-01	1.8464E-01	2.4953E-01
Location 404	1.0971E+02	1.8967E-01	1.5694E-01	1.1129E-01	1.5260E-01
Location 405	1.5934E+01	2.4729E-02	2.0277E-02	1.4349E-02	1.9676E-02
Location 406	1.8486E+01	3.3833E-02	2.8152E-02	2.0330E-02	2.7331E-02
Total					
IAEA Cf-252 reference	-----	2.5300E+00	1.4971E+00	1.2342E+00	2.5100E+00
BDMS (shutter open)					
Location 401	-----	1.0283E+01	5.4492E+00	4.5364E+00	9.4287E+00
Location 402	-----	9.0225E+00	4.8891E+00	4.0514E+00	8.3110E+00
Location 403	-----	1.0273E+00	7.0316E-01	5.5406E-01	9.6577E-01
Location 404	-----	2.6534E+00	1.4833E+00	1.2260E+00	2.4903E+00
Location 405	-----	1.8123E-01	1.0055E-01	8.2092E-02	1.6274E-01
Location 406	-----	1.1341E-01	7.7950E-02	6.1527E-02	1.0668E-01
BDMS (shutter closed)					
Location 401	-----	9.3977E+00	4.9992E+00	4.1640E+00	8.6626E+00
Location 402	-----	8.9420E+00	4.7567E+00	3.9521E+00	8.2015E+00
Location 403	-----	9.6469E-01	6.5491E-01	5.1625E-01	9.1063E-01
Location 404	-----	2.6827E+00	1.4761E+00	1.2245E+00	2.5146E+00
Location 405	-----	1.7806E-01	9.7070E-02	7.9424E-02	1.5982E-01
Location 406	-----	1.0586E-01	7.1960E-02	5.6858E-02	1.0005E-01

The calculated total equivalent dose rates at 1 meter from the source module of the BDMS mass flow monitor (locations 405 and 406) are below the Russian regulatory limit of 0.3 mrem/hr [17]:

Location	Largest calculated dose rate (mrem/hr)	Russian regulatory dose rate limit (mrem/hr)
405	0.18	0.3
406	0.11	0.3

The calculated total dose rates at the BDMS shielding surface are below the Russian regulatory limit of 10 mrem/hr [17] with the exception of the calculations using the 1977 fluence-to-dose conversion coefficients [15] for surface locations on the pipe axis, which is equal to the regulatory limit. At the time of the source installation an additional shielding was added to the BDMS, which is not accounted for in the present calculations. The statistical accuracy of the calculations using the COG code is better than 1% [31,32]. The agreement between COG calculations and the measurement is evaluated to be 5–10% [32].

Conclusion

The Monte Carlo calculations provided an accurate estimate of the neutron spectrum moderation outside the BDMS shielding, compared with an unmoderated ^{252}Cf source spectrum. Calculations of the dose rates with published U.S. and Russian fluence-to-dose conversion coefficients indicate that neutron dose rates in various locations outside the BDMS are overestimated by 25% to 55% compared with those from a bare unmoderated ^{252}Cf source. The results of the calculations support published data indicating that doses from neutrons with a moderated ^{252}Cf spectrum are overestimated when measured with a dose rate meter (e.g., rem ball) calibrated with a unmoderated (bare) ^{252}Cf source. In a variety of applications, the reported average dose overestimation is up to 65%, with the precise amount being dependent on the particular application [12]. Conservatively we can assume that in the neutron dose rate measurements outside the BDMS shielding, neutron dose rate overestimation is 25%. In other words, the actual neutron dose rate is at least 25% less than the dose rate directly determined from a dose rate meter calibrated with a bare Cf source. The calculations also showed that the total doses around BDMS are below the applicable Russian radiation safety regulatory limits.

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APPENDIX 1

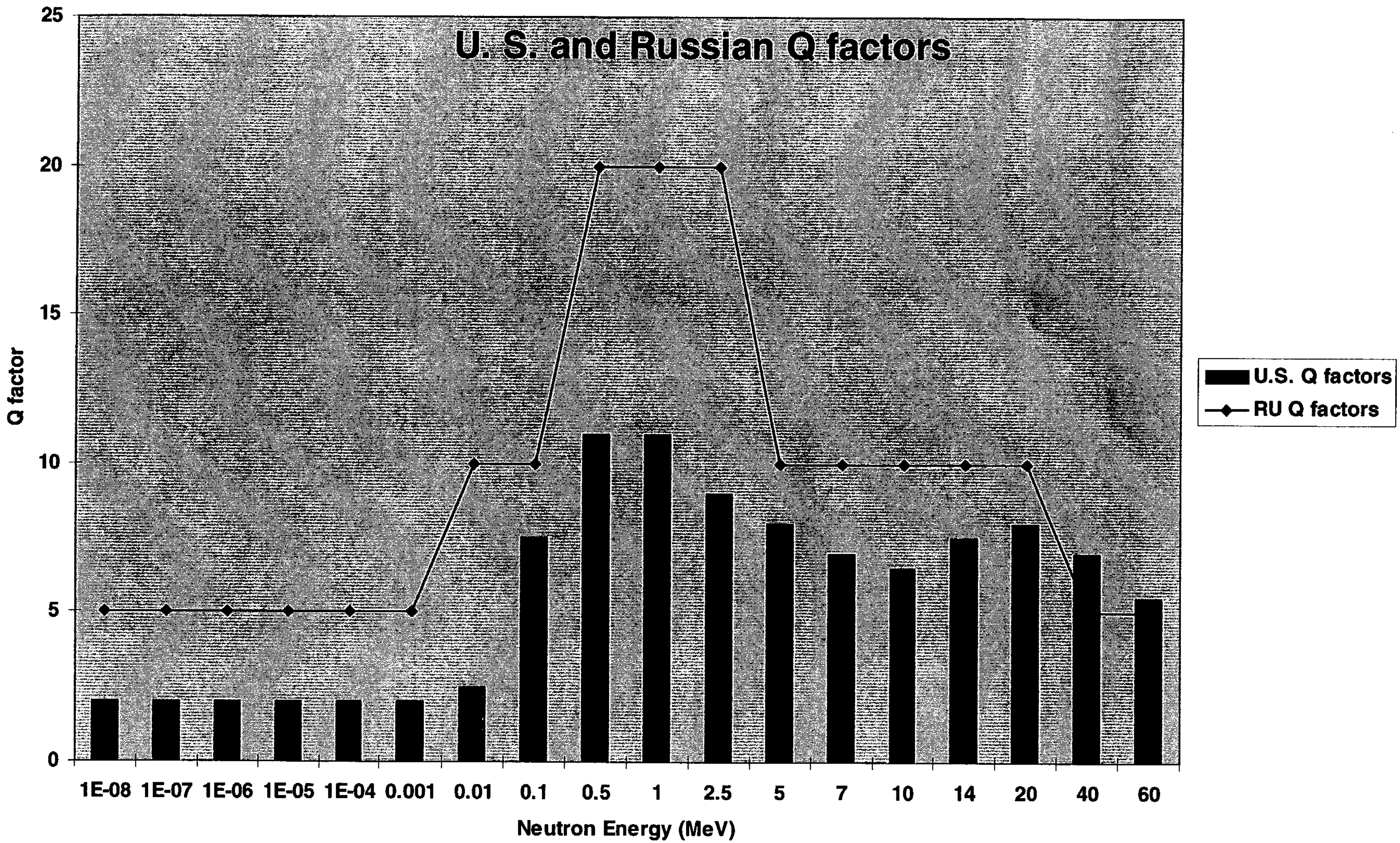
This Appendix has been included to indicate some of the problems and considerations involved in the selection and calibrations of dosimeters used in a neutron dosimetry program. There are number of review papers and proceedings of meetings on personnel neutron dosimetry [18–24]. The following text is excerpted from the latest ANSI standard on personnel neutron dosimeters [1].

In recent years there has been a great deal of controversy surrounding the best choice for the quality factor to be used for personnel exposures to neutrons. The National Council on Radiation Protection and Measurements (NCRP) recommended in Report 38 [25] a table of fluence to dose equivalent factors that were derived from an explicit relationship between the quality factor and the linear energy transfer (LET) of the secondary charged particles produced from neutron interactions in soft tissue. The report noted that a conservative assessment of the dose equivalent could be made by employing an approximate factor of 10.

In 1985, the International Committee for Radiation Protection (ICRP) recommended [26] an increase in the approximate value of the quality factor for neutrons by a factor of two based on more current information on the biological effectiveness of neutrons (see also the second note under Table 1). In 1987 the NCRP [27] endorsed this change and recommended that the factor of two be applied at all neutron energies. In 1993, the NCRP reaffirmed its 1987 recommendation and adopted the concept of the radiation weighting factor, w_e, proposed by the ICRP [28]. In a report [29] published by the International Commission on Radiation Units and measurements (ICRU), a joint ICRU/ICRP Task Group recommended a new definition of the quality factor in terms of the linear energy of the secondary charged particles produced from neutron interactions with ICRU tissue.

In June 1995, the Committee on Interagency Radiation Research and Policy Coordination (CIRRPC) reviewed the controversy surrounding the appropriate choice of the quality factor and recommended that "present values of the absorbed dose or dose equivalent relationships for neutrons, nominally Q_n value of 10, by Federal agencies should be maintained until such as need for change is firmly established." [30]. The recommended increase in the quality factor remains controversial.

Figure 1



U. S. and Russian Q factors
25
20
15
10
5
0
Q factor
1E-08
1E-07
1E-06
1E-05
1E-04
0.001
0.01
0.1
0.5
1
2.5
5
7
10
14
20
40
60
Neutron Energy (MeV)
U.S. Q factors
RU Q factors

Figure 2

BDMS source module and shielding

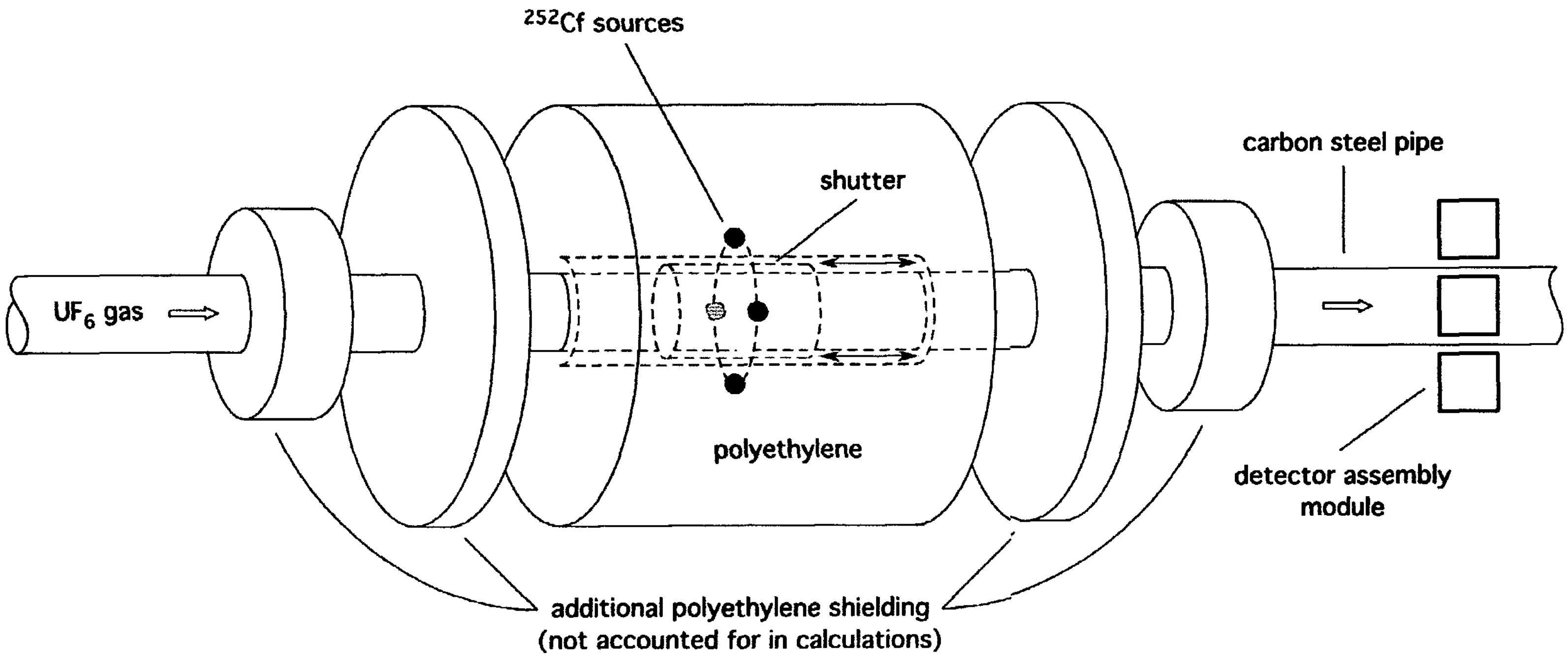


Figure 3

Radial cross-section view of the BDMS flow monitor's source module assembly.

Figure 4

Cross-section view (top) of the BDMS flow monitor's source module assembly

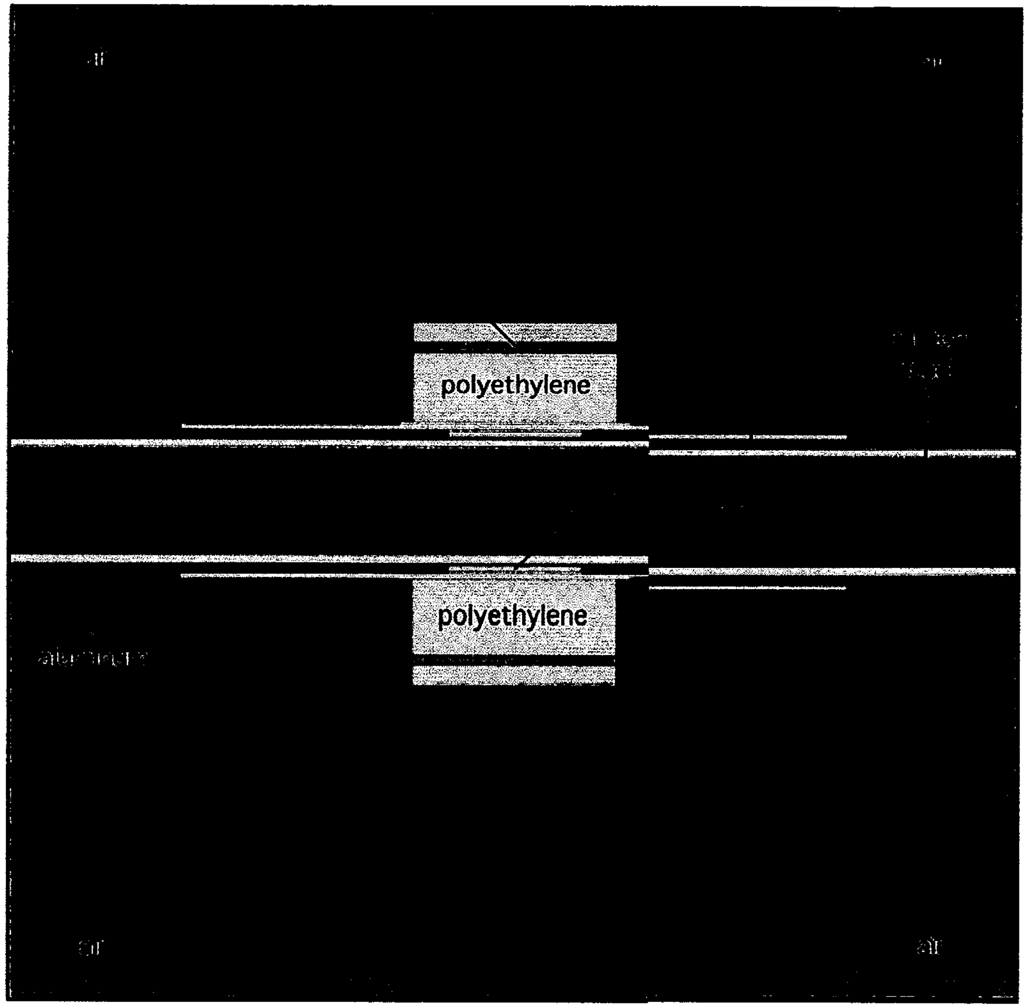


Figure 5

Locations around BDMS UF6 mass flow meter where neutron and gamma spectra and dose rates were calculated

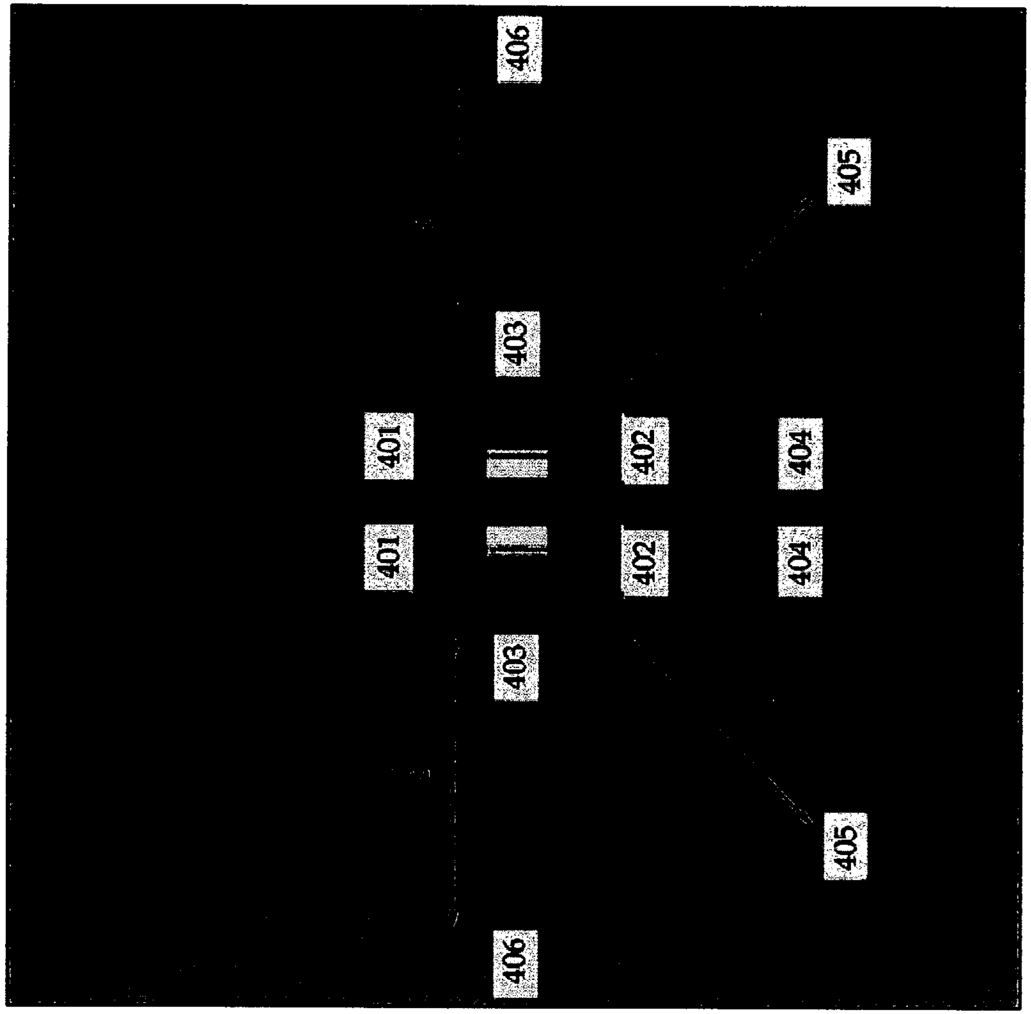
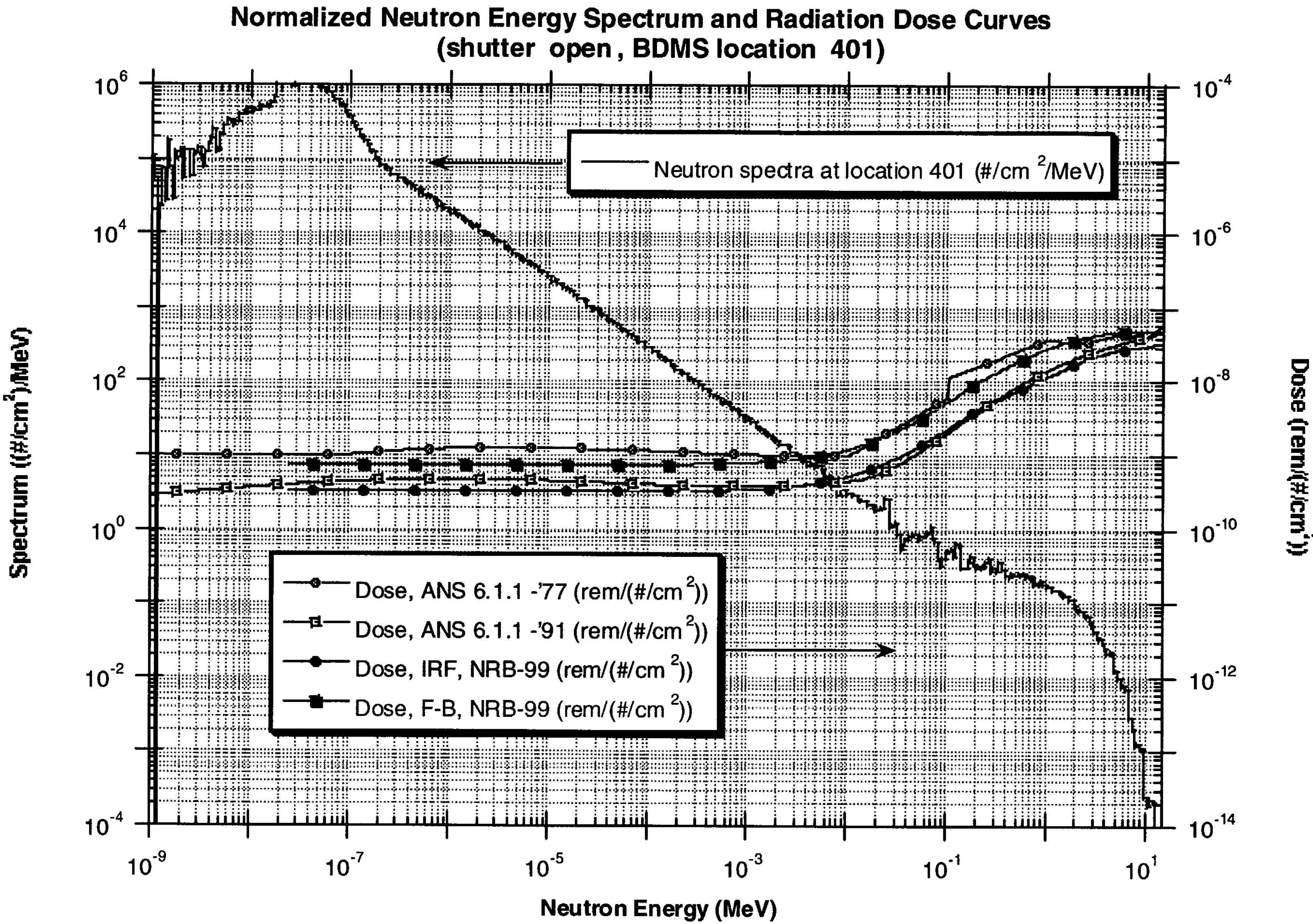
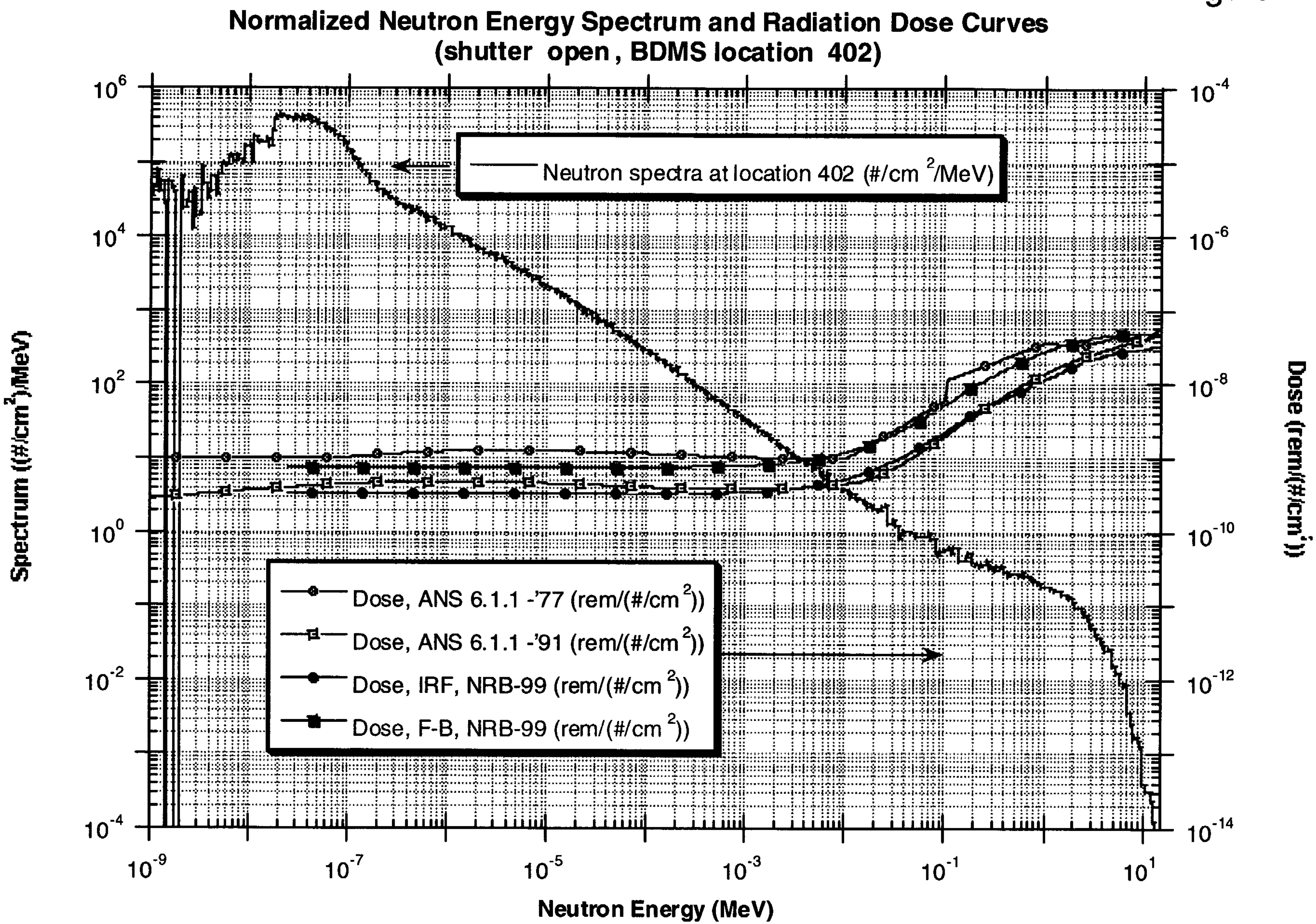


Figure 6



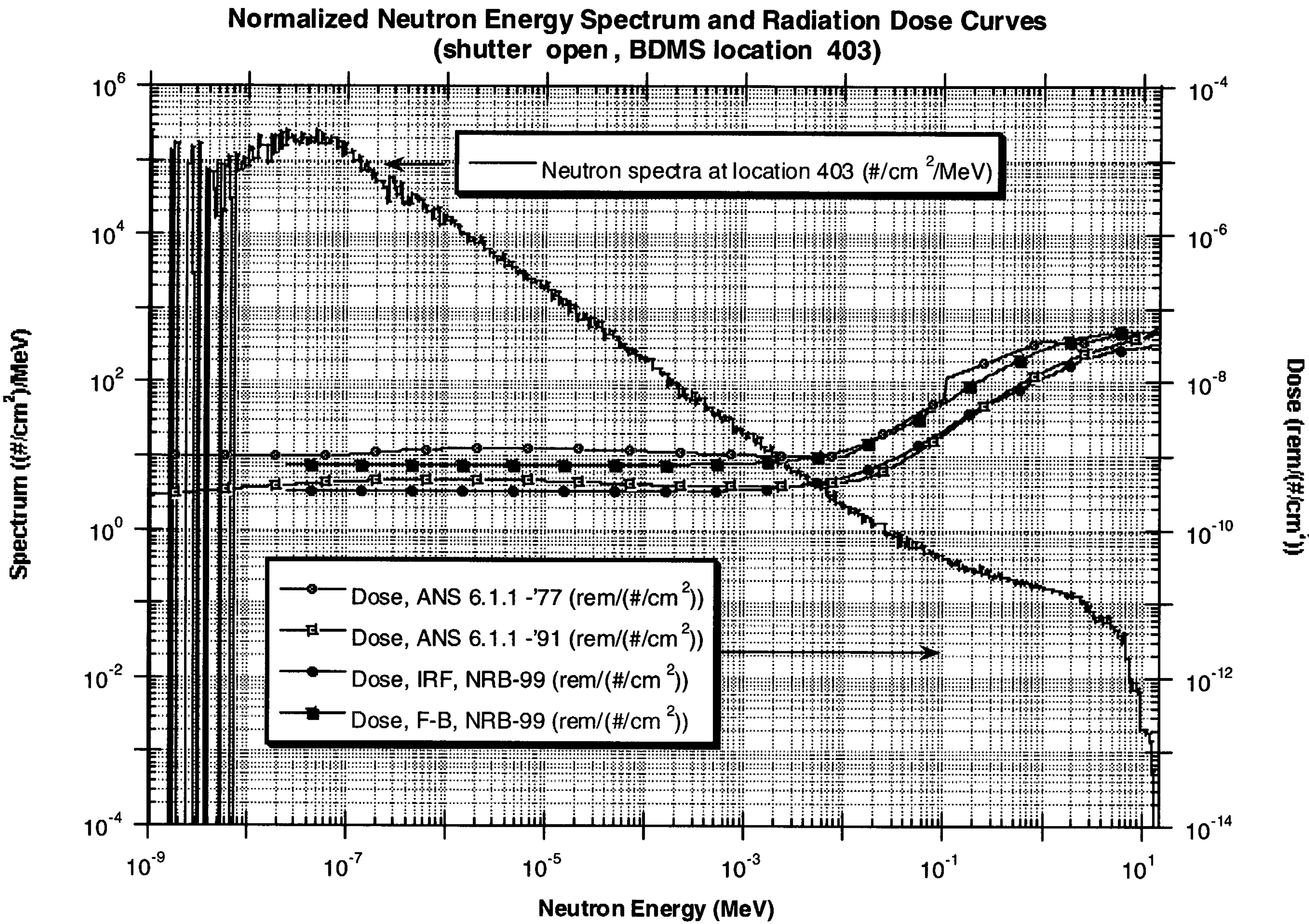
Normalized Neutron Energy Spectrum and Radiation Dose Curves
(shutter open, BDMS location 401)
Neutron spectra at location 401 (#/cm 2/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm 2))
Dose, ANS 6.1.1 -'91 (rem/(#/cm 2))
Dose, IRF, NRB-99 (rem/(#/cm 2))
Dose, F-B, NRB-99 (rem/(#/cm 2))
Spectrum ((#/cm2)/MeV)
Dose (rem/(#/cm2))
Neutron Energy (MeV)
10^6
10^4
10^2
10^0
10^-2
10^-4
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
10^-9
10^-7
10^-5
10^-3
10^-1
10^1

Figure 7



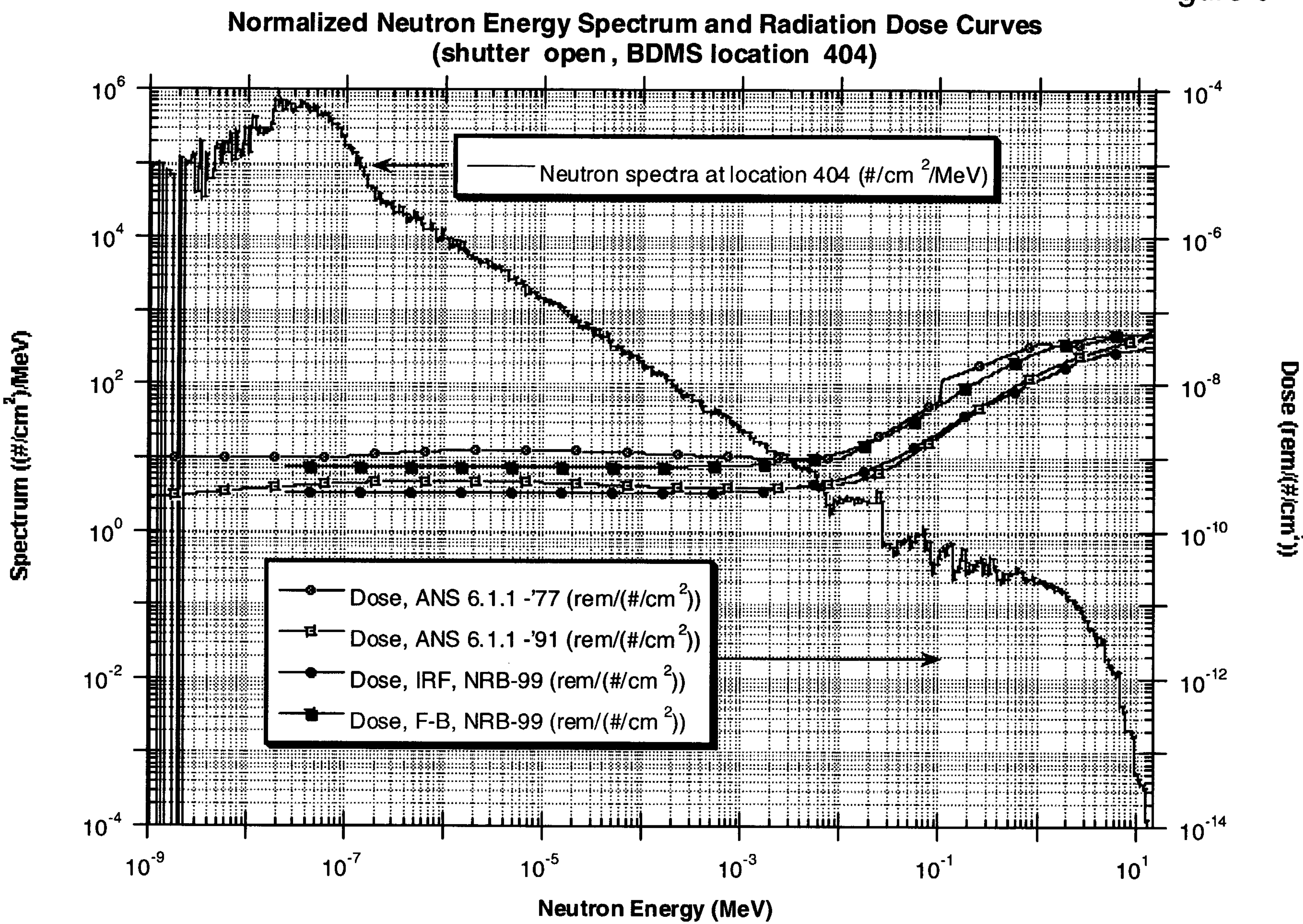
Normalized Neutron Energy Spectrum and Radiation Dose Curves
(shutter open, BDMS location 402)
Neutron spectra at location 402 (#/cm 2/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm 2))
Dose, ANS 6.1.1 -'91 (rem/(#/cm 2))
Dose, IRF, NRB-99 (rem/(#/cm 2))
Dose, F-B, NRB-99 (rem/(#/cm 2))
Spectrum ((#/cm2)/MeV)
Dose (rem/(#/cm2))
Neutron Energy (MeV)
10^6
10^4
10^2
10^0
10^-2
10^-4
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
10^-9
10^-7
10^-5
10^-3
10^-1
10^1

Figure 8



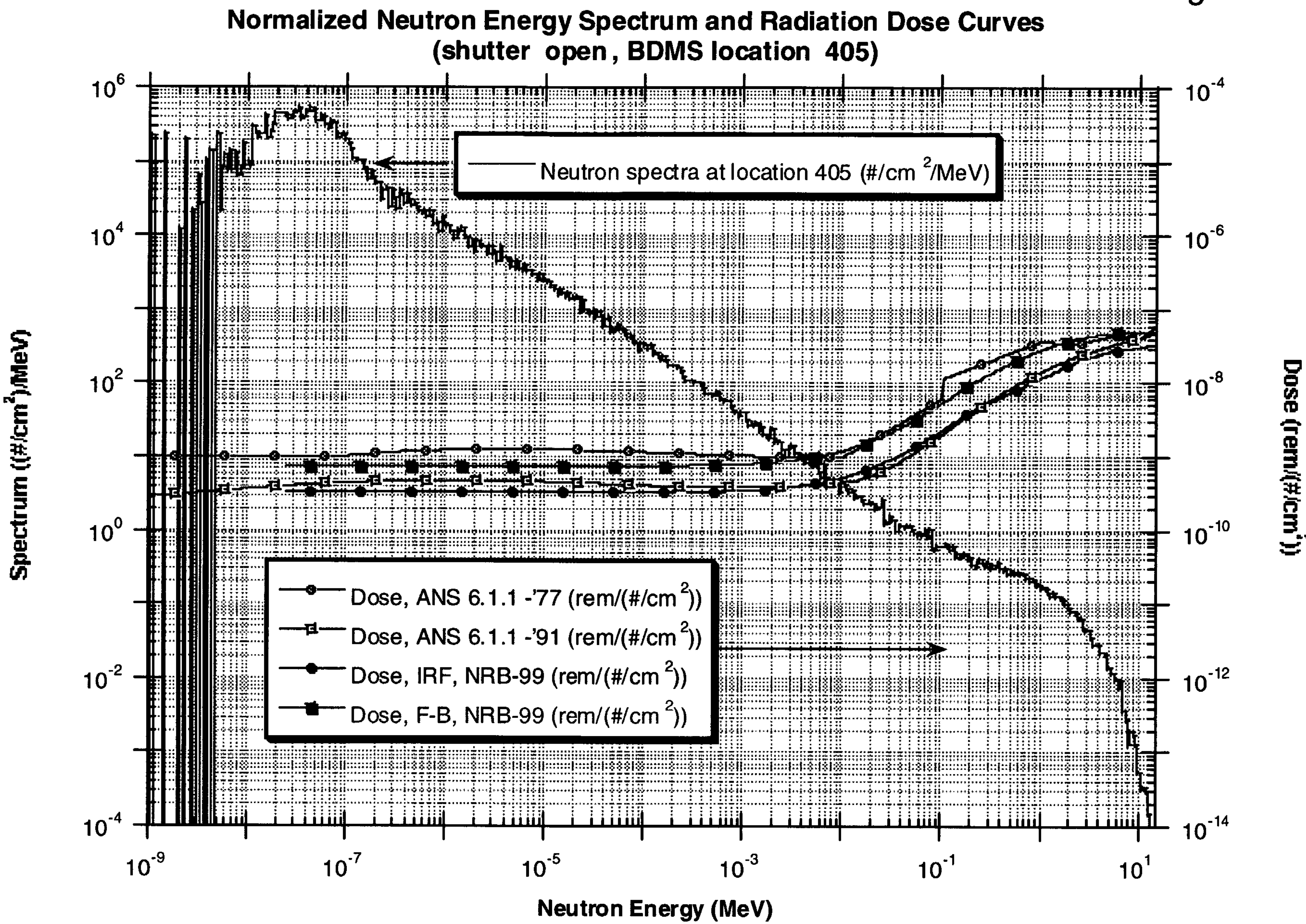
Normalized Neutron Energy Spectrum and Radiation Dose Curves
(shutter open , BDMS location 403)
Neutron spectra at location 403 (#/cm 2/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm 2))
Dose, ANS 6.1.1 -'91 (rem/(#/cm 2))
Dose, IRF, NRB-99 (rem/(#/cm 2))
Dose, F-B, NRB-99 (rem/(#/cm 2))
Spectrum ((#/cm2)/MeV)
Dose (rem/(#/cm2))
Neutron Energy (MeV)
10^6
10^4
10^2
10^0
10^-2
10^-4
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
10^-9
10^-7
10^-5
10^-3
10^-1
10^1

Figure 9



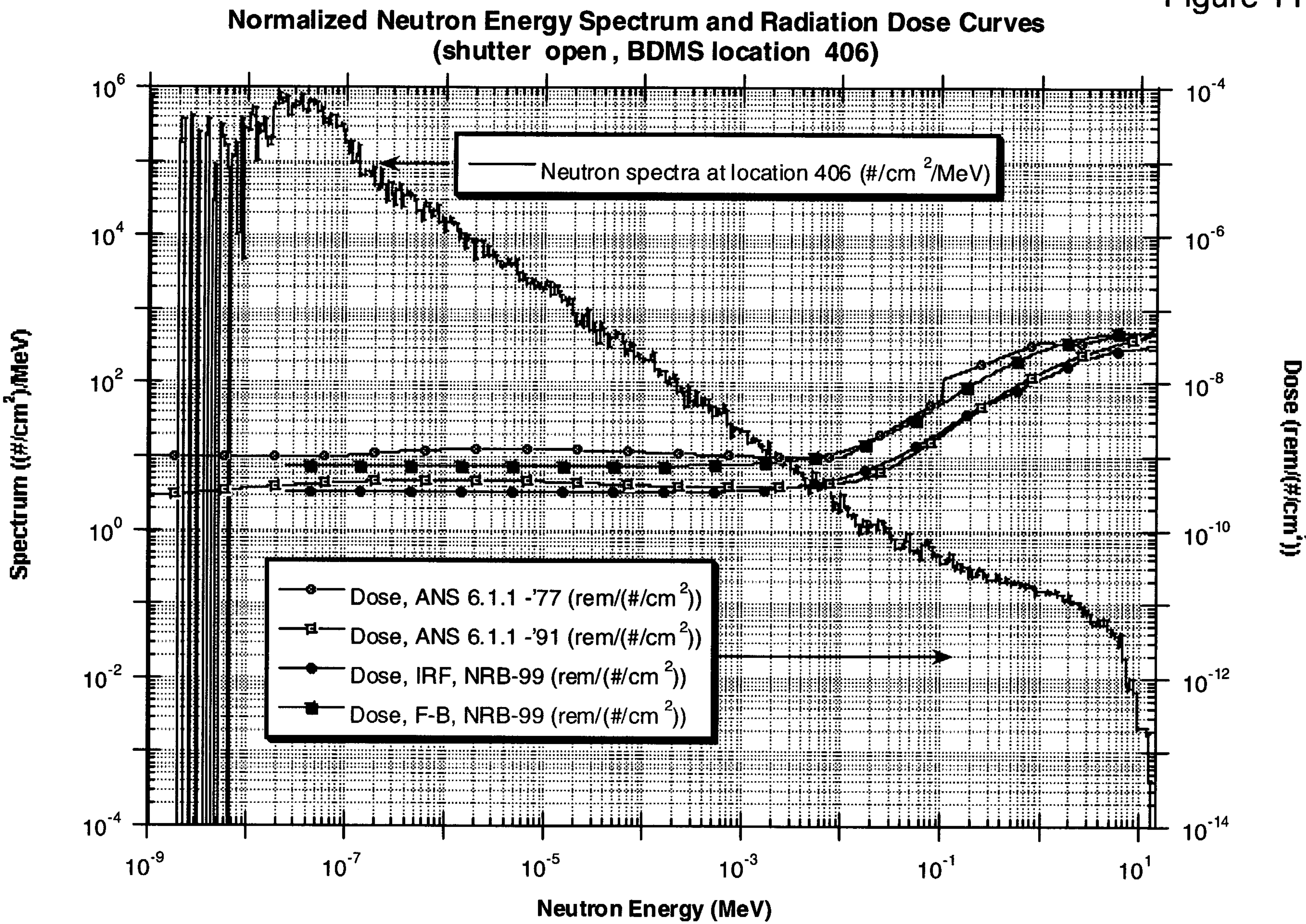
Normalized Neutron Energy Spectrum and Radiation Dose Curves
(shutter open, BDMS location 404)
Neutron spectra at location 404 (#/cm 2/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm 2))
Dose, ANS 6.1.1 -'91 (rem/(#/cm 2))
Dose, IRF, NRB-99 (rem/(#/cm 2))
Dose, F-B, NRB-99 (rem/(#/cm 2))
Spectrum ((#/cm2)/MeV)
Dose (rem/(#/cm2))
Neutron Energy (MeV)
10^6
10^4
10^2
10^0
10^-2
10^-4
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
10^-9
10^-7
10^-5
10^-3
10^-1
10^1

Figure 10



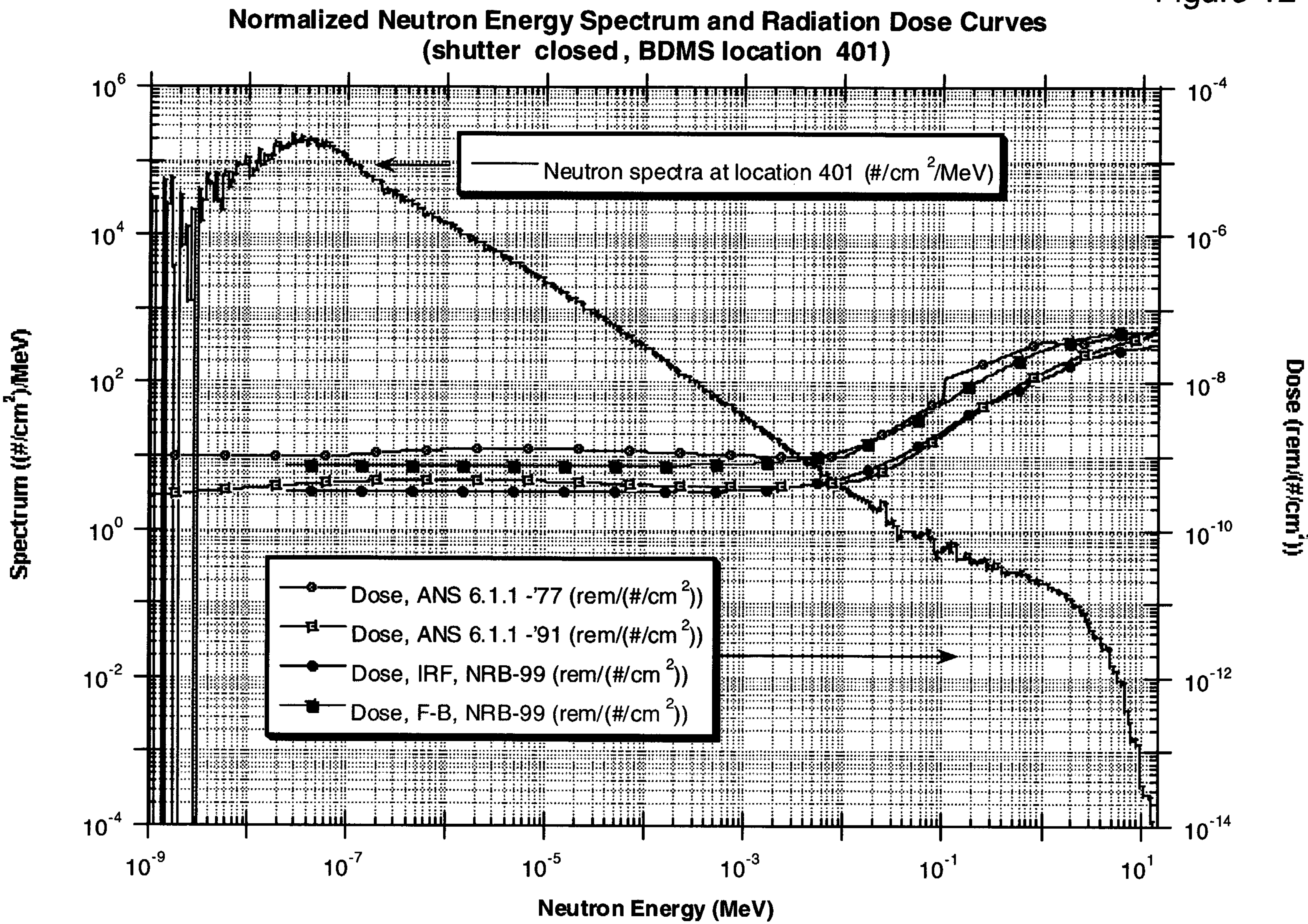
Normalized Neutron Energy Spectrum and Radiation Dose Curves
(shutter open, BDMS location 405)
Neutron spectra at location 405 (#/cm 2/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm 2))
Dose, ANS 6.1.1 -'91 (rem/(#/cm 2))
Dose, IRF, NRB-99 (rem/(#/cm 2))
Dose, F-B, NRB-99 (rem/(#/cm 2))
Spectrum ((#/cm2)/MeV)
Dose (rem/(#/cm2))
Neutron Energy (MeV)

Figure 11



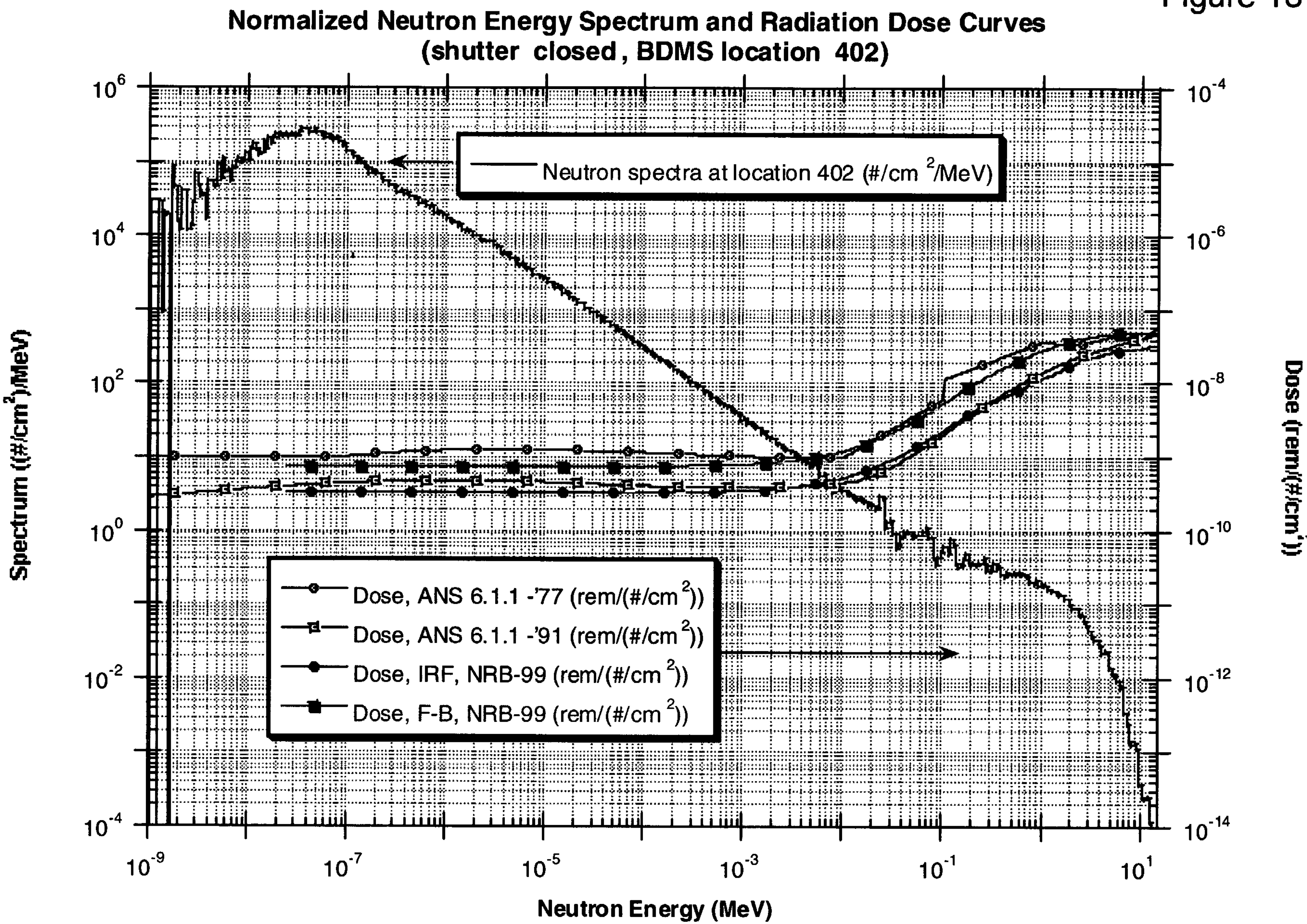
Normalized Neutron Energy Spectrum and Radiation Dose Curves
(shutter open, BDMS location 406)
Neutron spectra at location 406 (#/cm 2/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm 2))
Dose, ANS 6.1.1 -'91 (rem/(#/cm 2))
Dose, IRF, NRB-99 (rem/(#/cm 2))
Dose, F-B, NRB-99 (rem/(#/cm 2))
Spectrum ((#/cm2)/MeV)
Dose (rem/(#/cm2))
Neutron Energy (MeV)
10^6
10^4
10^2
10^0
10^-2
10^-4
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
10^-9
10^-7
10^-5
10^-3
10^-1
10^1

Figure 12



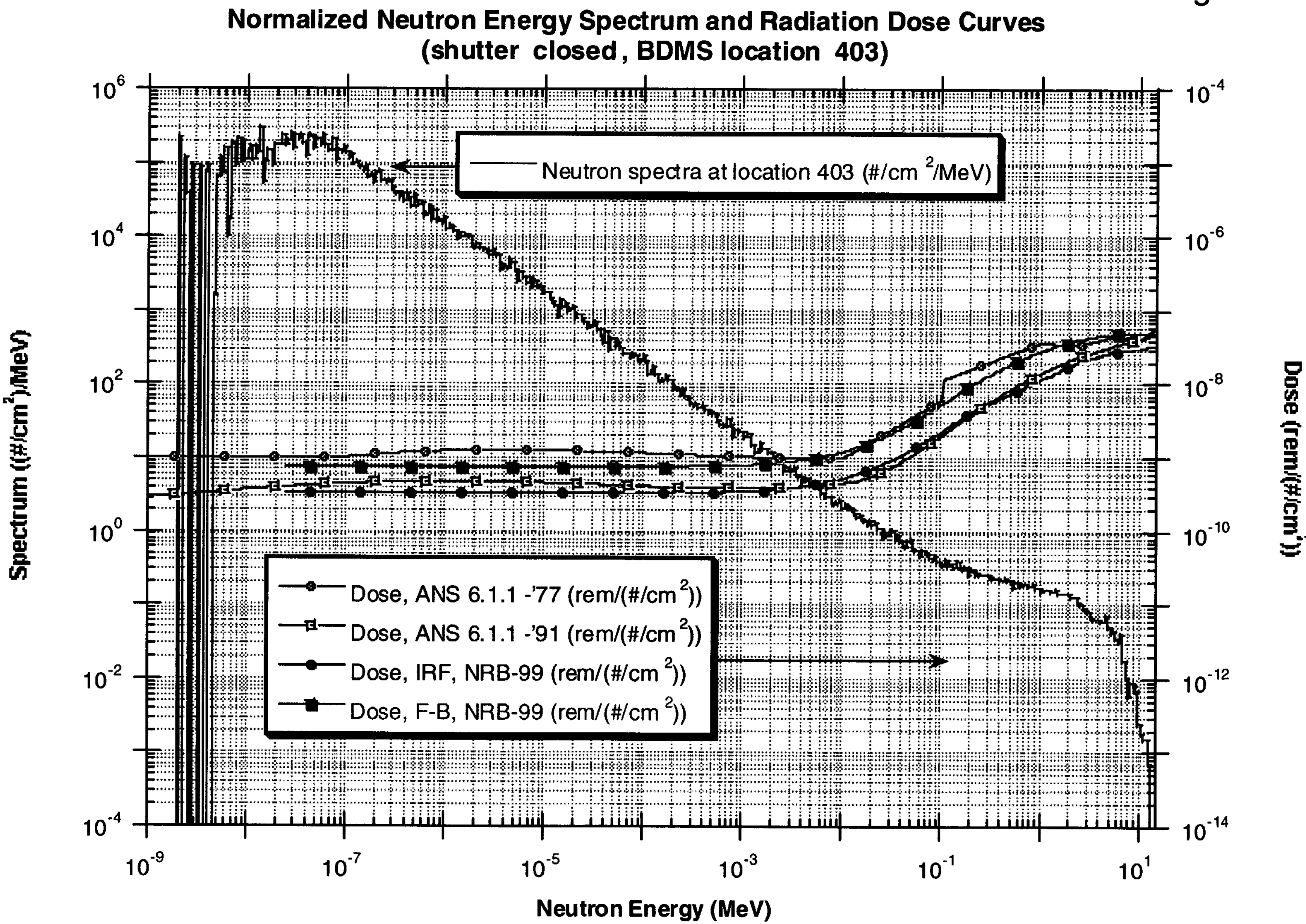
Normalized Neutron Energy Spectrum and Radiation Dose Curves
(shutter closed, BDMS location 401)
Neutron spectra at location 401 (#/cm²/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm²))
Dose, ANS 6.1.1 -'91 (rem/(#/cm²))
Dose, IRF, NRB-99 (rem/(#/cm²))
Dose, F-B, NRB-99 (rem/(#/cm²))
Spectrum ((#/cm²)/MeV)
Dose (rem/(#/cm²))
Neutron Energy (MeV)
10^6
10^4
10^2
10^0
10^-2
10^-4
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
10^-9
10^-7
10^-5
10^-3
10^-1
10^1

Figure 13



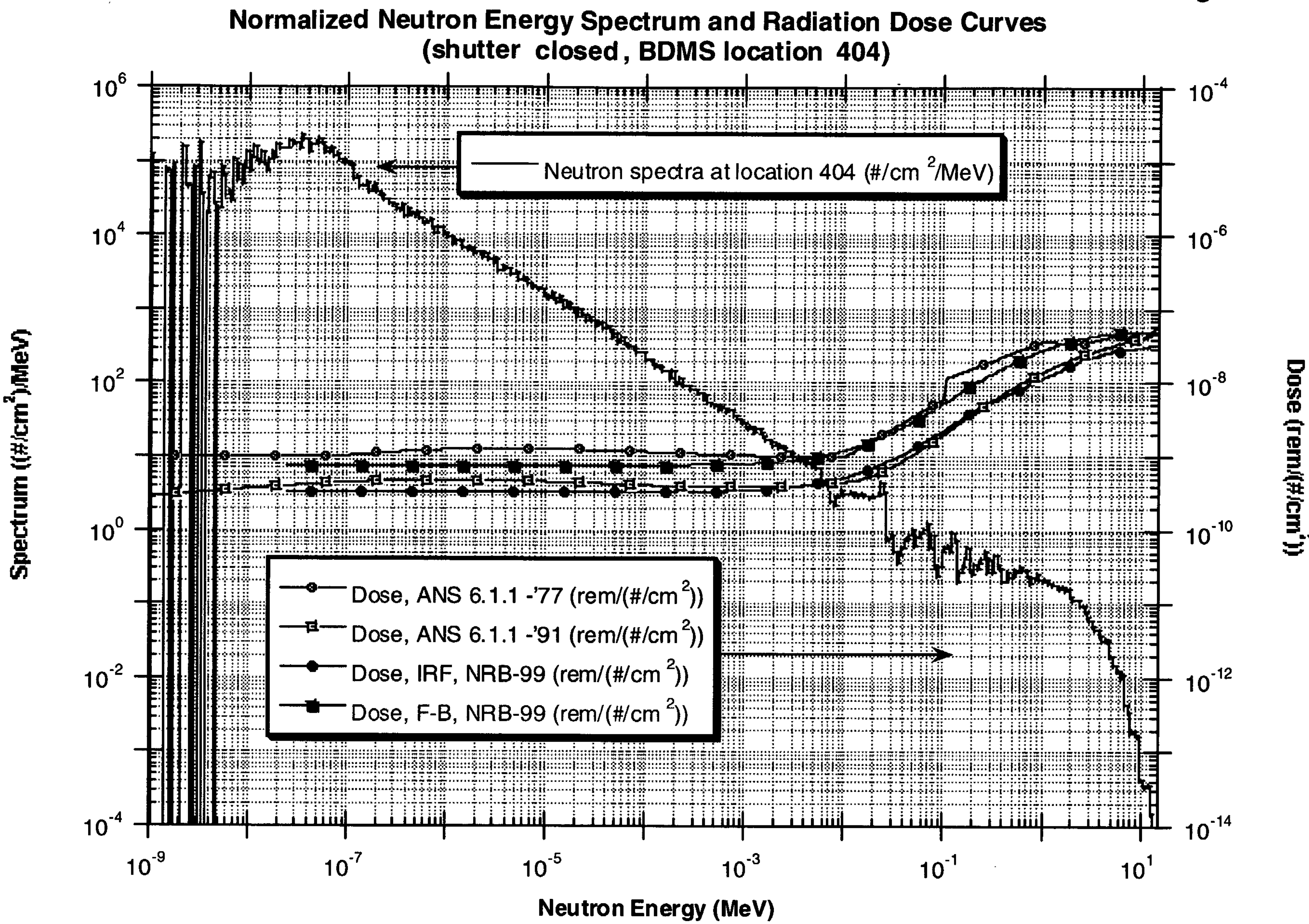
Normalized Neutron Energy Spectrum and Radiation Dose Curves
(shutter closed, BDMS location 402)
Neutron spectra at location 402 (#/cm 2/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm 2))
Dose, ANS 6.1.1 -'91 (rem/(#/cm 2))
Dose, IRF, NRB-99 (rem/(#/cm 2))
Dose, F-B, NRB-99 (rem/(#/cm 2))
Spectrum ((#/cm2)/MeV)
Dose (rem/(#/cm2))
Neutron Energy (MeV)
10-9
10-7
10-5
10-3
10-1
101
106
104
102
100
10-2
10-4
10-4
10-6
10-8
10-10
10-12
10-14

Figure 14



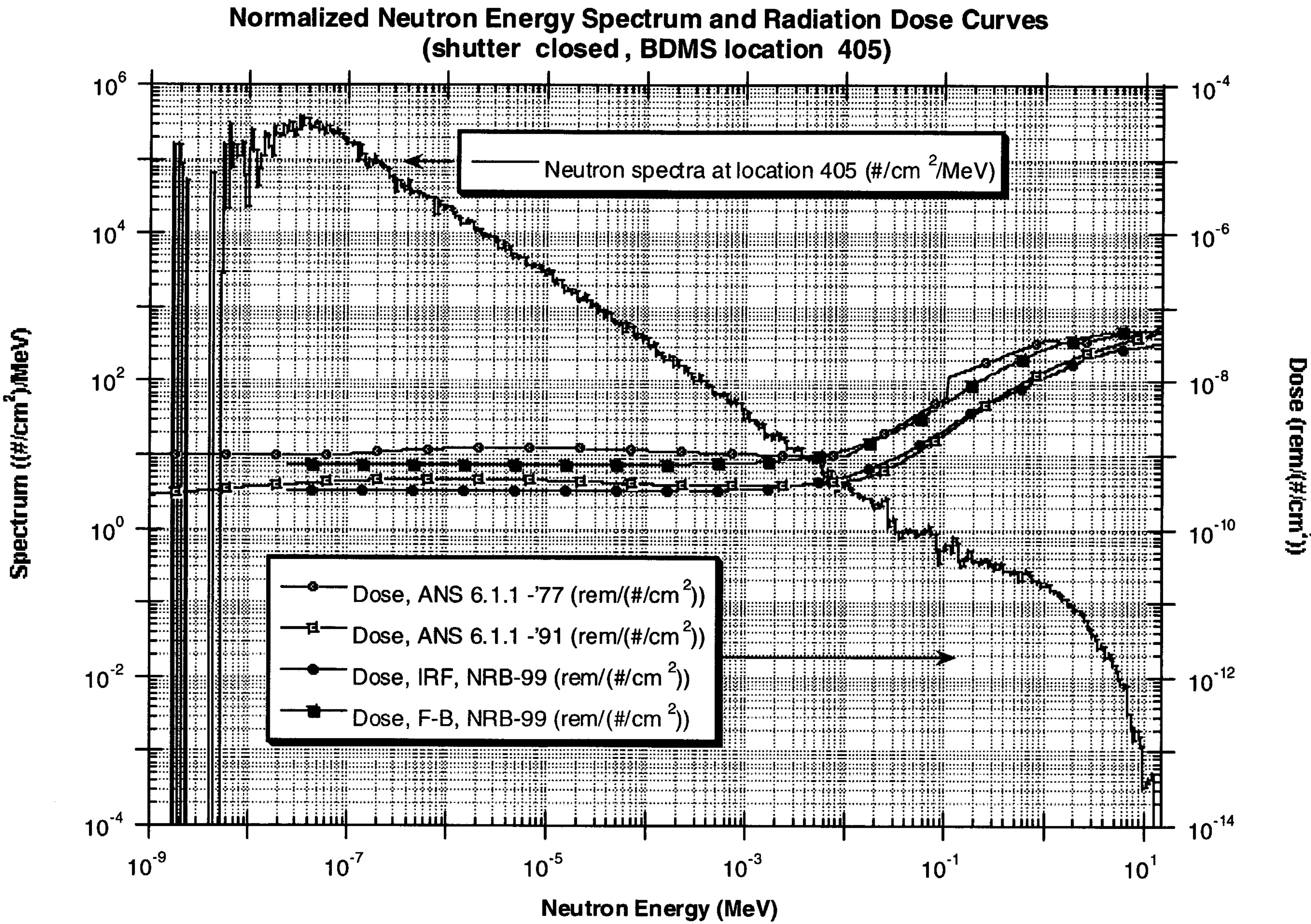
Normalized Neutron Energy Spectrum and Radiation Dose Curves
(shutter closed, BDMS location 403)
Neutron spectra at location 403 (#/cm 2/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm 2))
Dose, ANS 6.1.1 -'91 (rem/(#/cm 2))
Dose, IRF, NRB-99 (rem/(#/cm 2))
Dose, F-B, NRB-99 (rem/(#/cm 2))
Spectrum ((#/cm 2)/MeV)
Dose (rem/(#/cm 2))
Neutron Energy (MeV)
10^6
10^4
10^2
10^0
10^-2
10^-4
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
10^-9
10^-7
10^-5
10^-3
10^-1
10^1

Figure 15



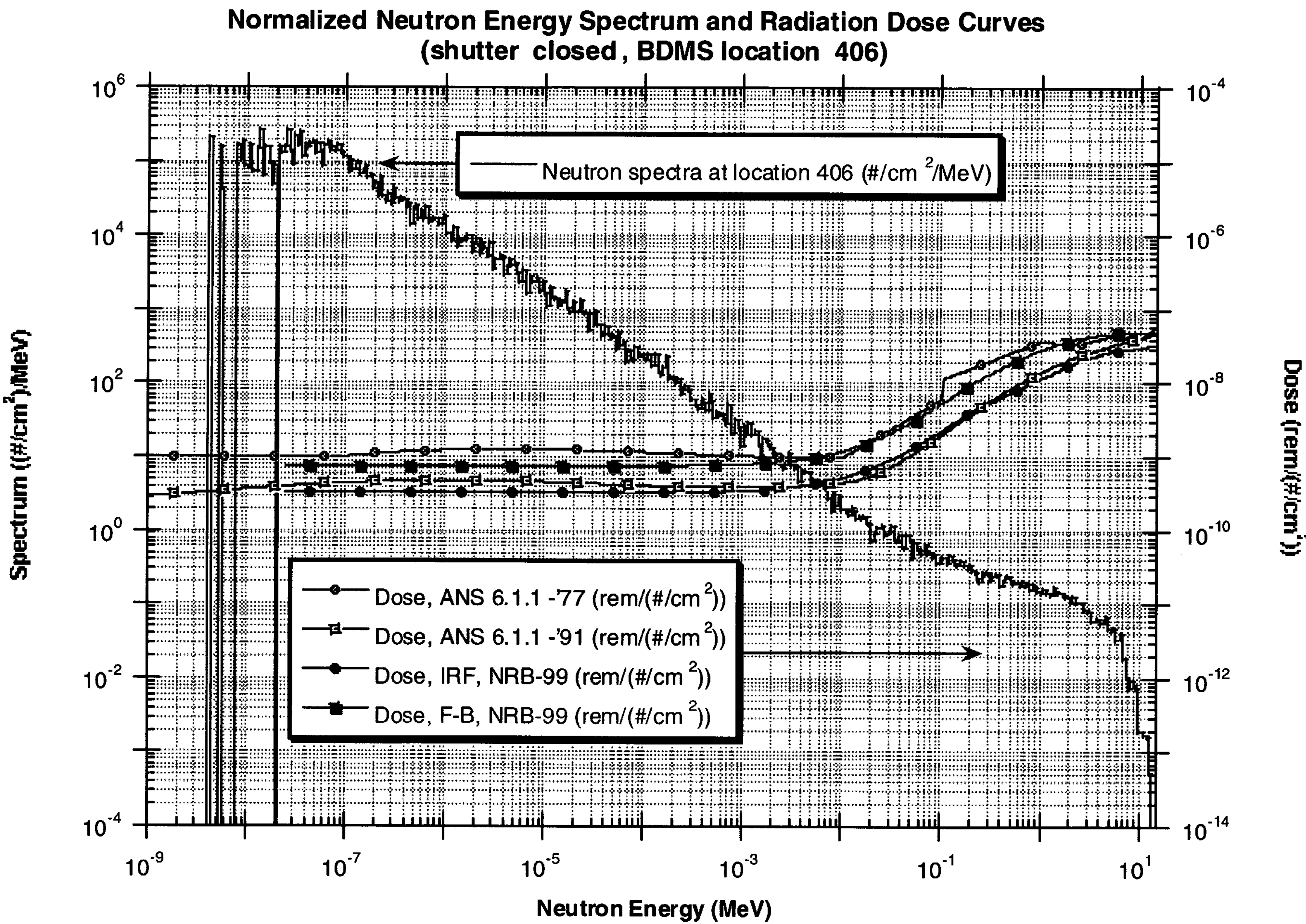
Normalized Neutron Energy Spectrum and Radiation Dose Curves
(shutter closed, BDMS location 404)
Neutron spectra at location 404 (#/cm 2/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm 2))
Dose, ANS 6.1.1 -'91 (rem/(#/cm 2))
Dose, IRF, NRB-99 (rem/(#/cm 2))
Dose, F-B, NRB-99 (rem/(#/cm 2))
Spectrum ((#/cm 2)/MeV)
Dose (rem/(#/cm 2))
Neutron Energy (MeV)
10^6
10^4
10^2
10^0
10^-2
10^-4
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
10^-9
10^-7
10^-5
10^-3
10^-1
10^1

Figure 16



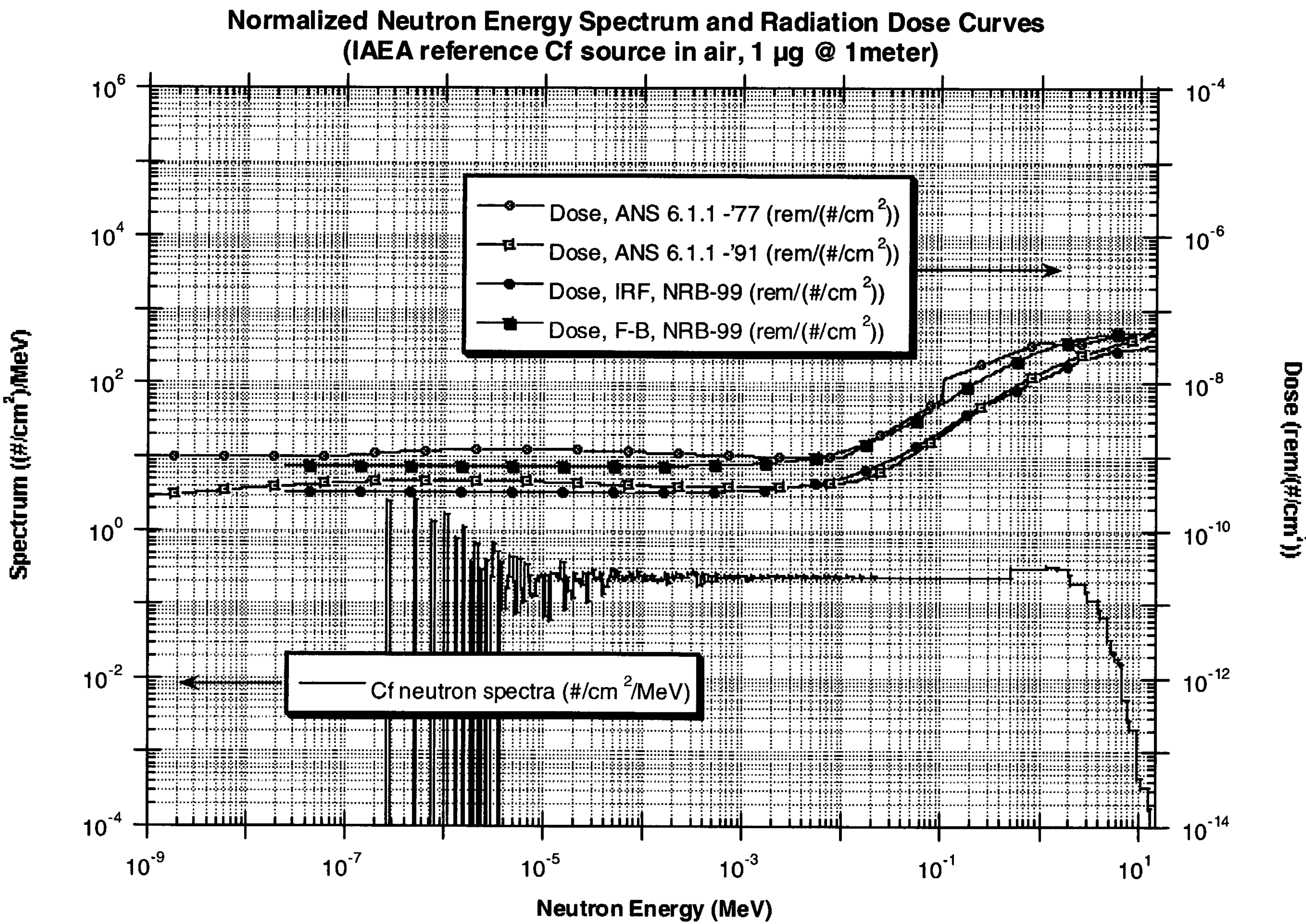
Normalized Neutron Energy Spectrum and Radiation Dose Curves
(shutter closed, BDMS location 405)
Neutron spectra at location 405 (#/cm 2/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm 2))
Dose, ANS 6.1.1 -'91 (rem/(#/cm 2))
Dose, IRF, NRB-99 (rem/(#/cm 2))
Dose, F-B, NRB-99 (rem/(#/cm 2))
Spectrum ((#/cm2)/MeV)
Dose (rem/(#/cm2))
Neutron Energy (MeV)
10^6
10^4
10^2
10^0
10^-2
10^-4
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
10^-9
10^-7
10^-5
10^-3
10^-1
10^1

Figure 17



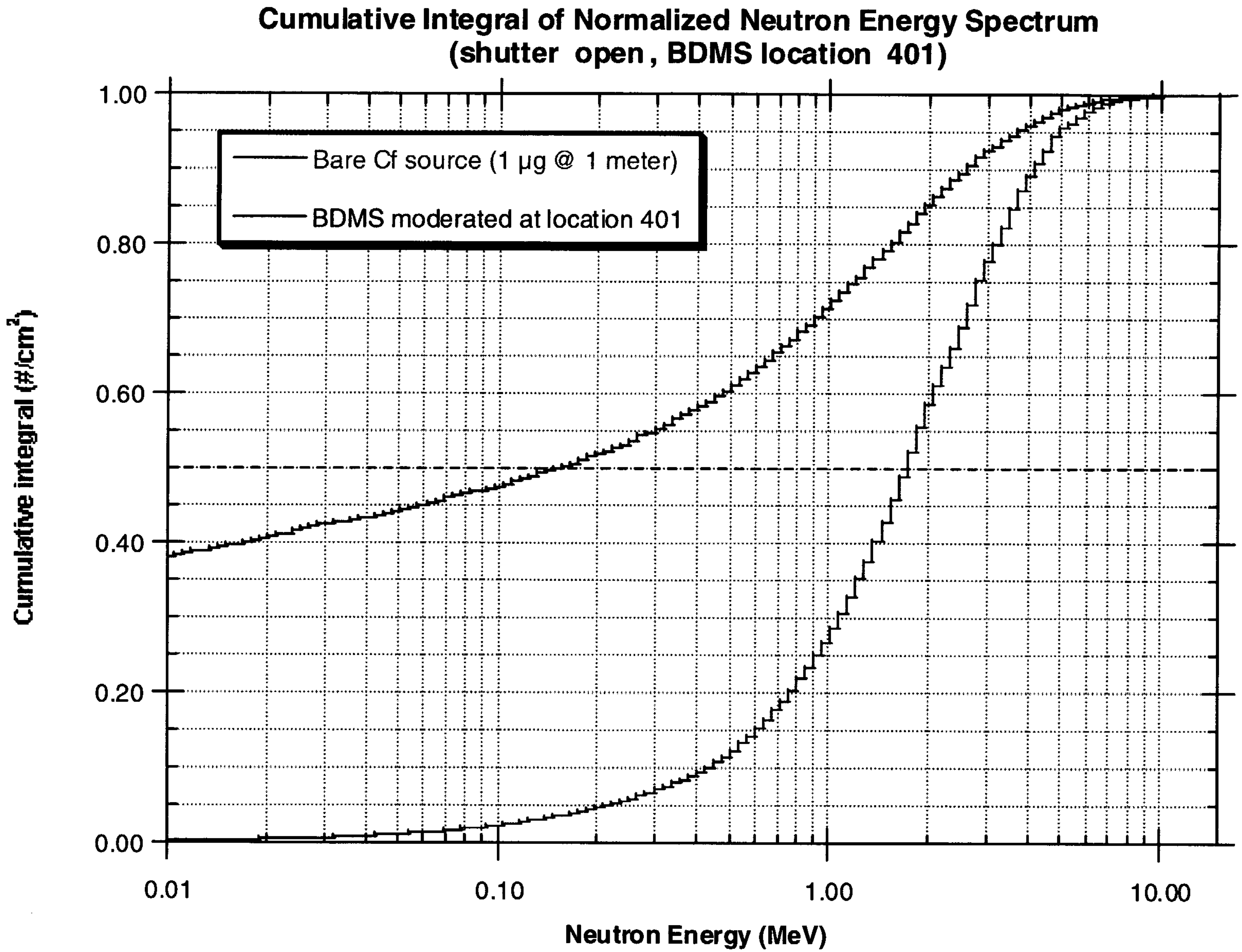
Normalized Neutron Energy Spectrum and Radiation Dose Curves
(shutter closed, BDMS location 406)
Neutron spectra at location 406 (#/cm 2/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm 2))
Dose, ANS 6.1.1 -'91 (rem/(#/cm 2))
Dose, IRF, NRB-99 (rem/(#/cm 2))
Dose, F-B, NRB-99 (rem/(#/cm 2))
Spectrum ((#/cm2)/MeV)
Dose (rem/(#/cm2))
Neutron Energy (MeV)

Figure 18



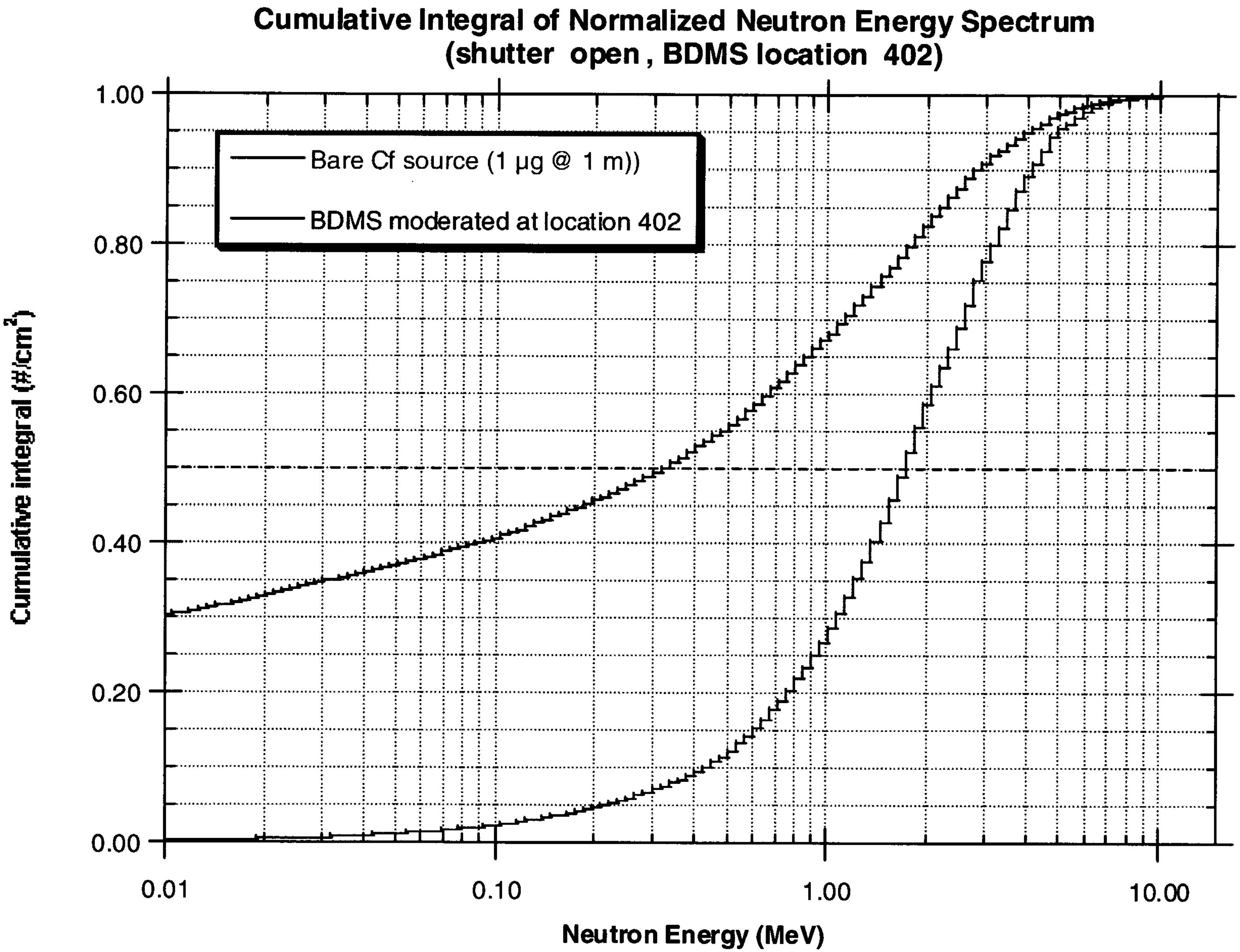
Normalized Neutron Energy Spectrum and Radiation Dose Curves
(IAEA reference Cf source in air, 1 µg @ 1meter)
Dose, ANS 6.1.1 -'77 (rem/(#/cm 2))
Dose, ANS 6.1.1 -'91 (rem/(#/cm 2))
Dose, IRF, NRB-99 (rem/(#/cm 2))
Dose, F-B, NRB-99 (rem/(#/cm 2))
Cf neutron spectra (#/cm 2/MeV)
Spectrum ((#/cm 2)/MeV)
Dose (rem/(#/cm 2))
Neutron Energy (MeV)
10^6
10^4
10^2
10^0
10^-2
10^-4
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
10^-9
10^-7
10^-5
10^-3
10^-1
10^1

Figure 19



Cumulative Integral of Normalized Neutron Energy Spectrum
(shutter open, BDMS location 401)
Bare Cf source (1 µg @ 1 meter)
BDMS moderated at location 401
Cumulative integral (#/cm²)
1.00
0.80
0.60
0.40
0.20
0.00
0.01
0.10
1.00
10.00
Neutron Energy (MeV)

Figure 20



Cumulative Integral of Normalized Neutron Energy Spectrum
(shutter open , BDMS location 402)
Bare Cf source (1 μg @ 1 m))
BDMS moderated at location 402
Cumulative integral (#/cm^2)
1.00
0.80
0.60
0.40
0.20
0.00
0.01
0.10
1.00
10.00
Neutron Energy (MeV)

Figure 21

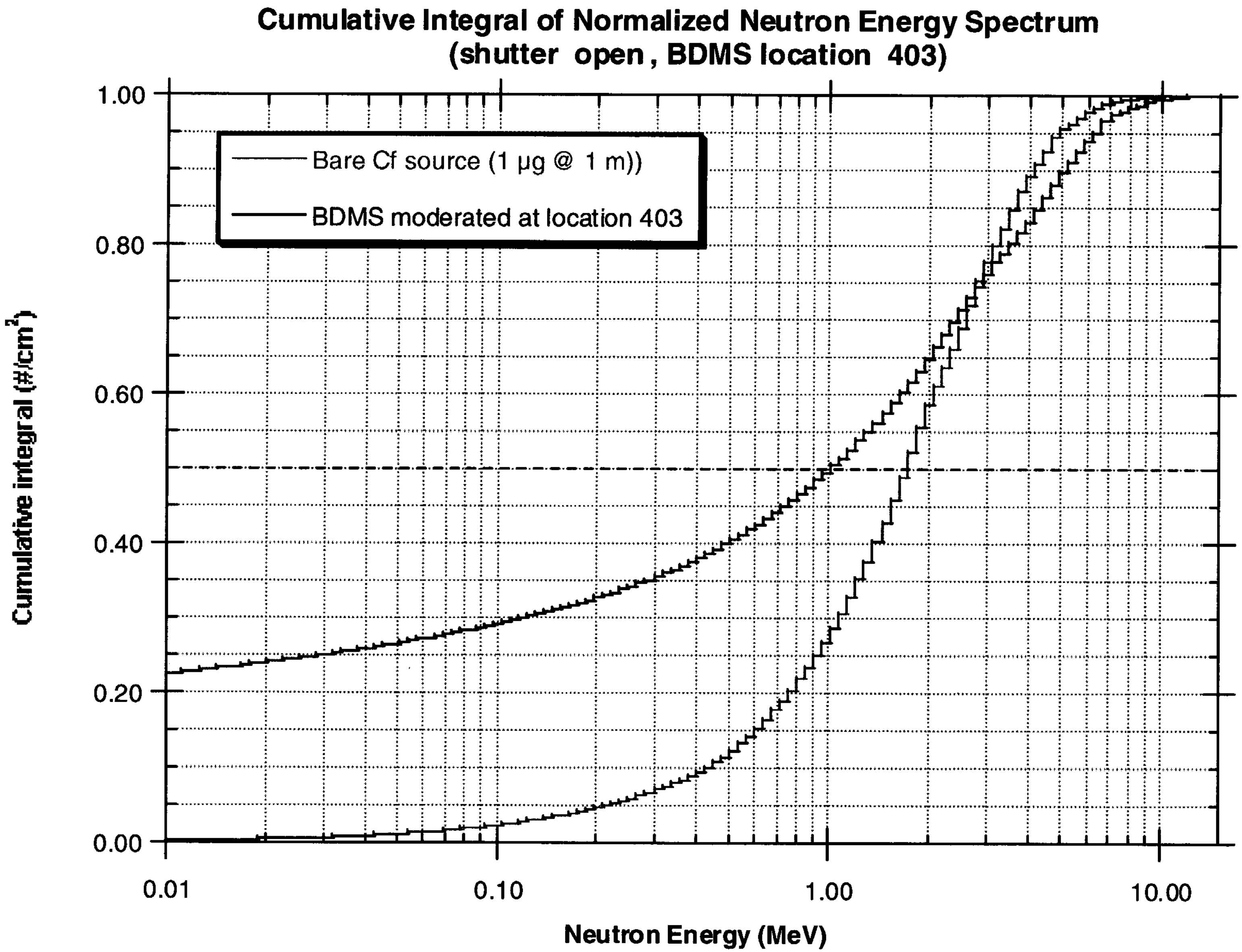
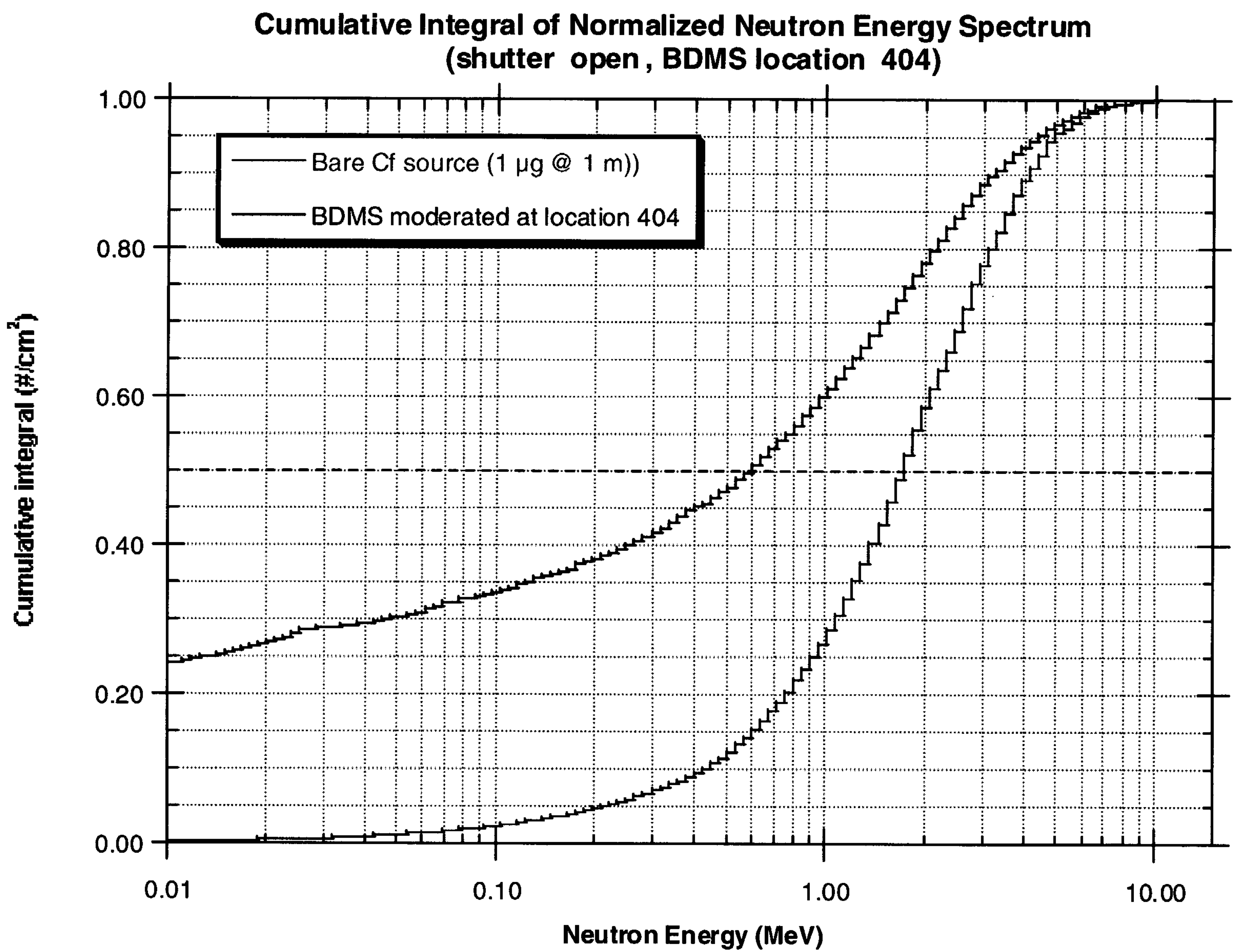

Cumulative Integral of Normalized Neutron Energy Spectrum
(shutter open , BDMS location 403)
Bare Cf source (1 µg @ 1 m))
BDMS moderated at location 403
Cumulative integral (#/cm²)
Neutron Energy (MeV)
1.00
0.80
0.60
0.40
0.20
0.00
0.01
0.10
1.00
10.00

Figure 22



Cumulative Integral of Normalized Neutron Energy Spectrum
(shutter open, BDMS location 404)
Bare Cf source (1 µg @ 1 m))
BDMS moderated at location 404
Cumulative integral (#/cm²)
1.00
0.80
0.60
0.40
0.20
0.00
0.01
0.10
1.00
10.00
Neutron Energy (MeV)

Figure 23

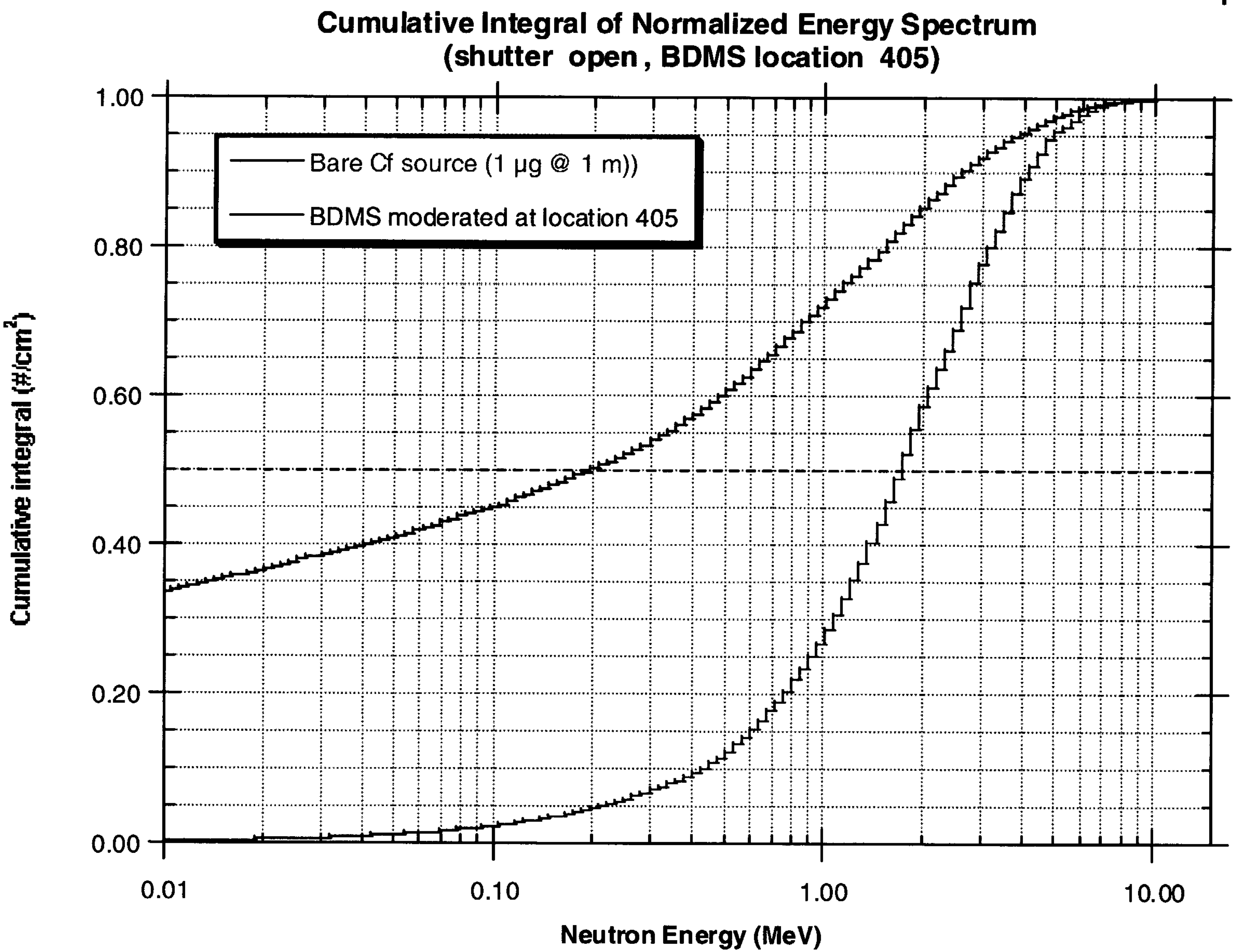
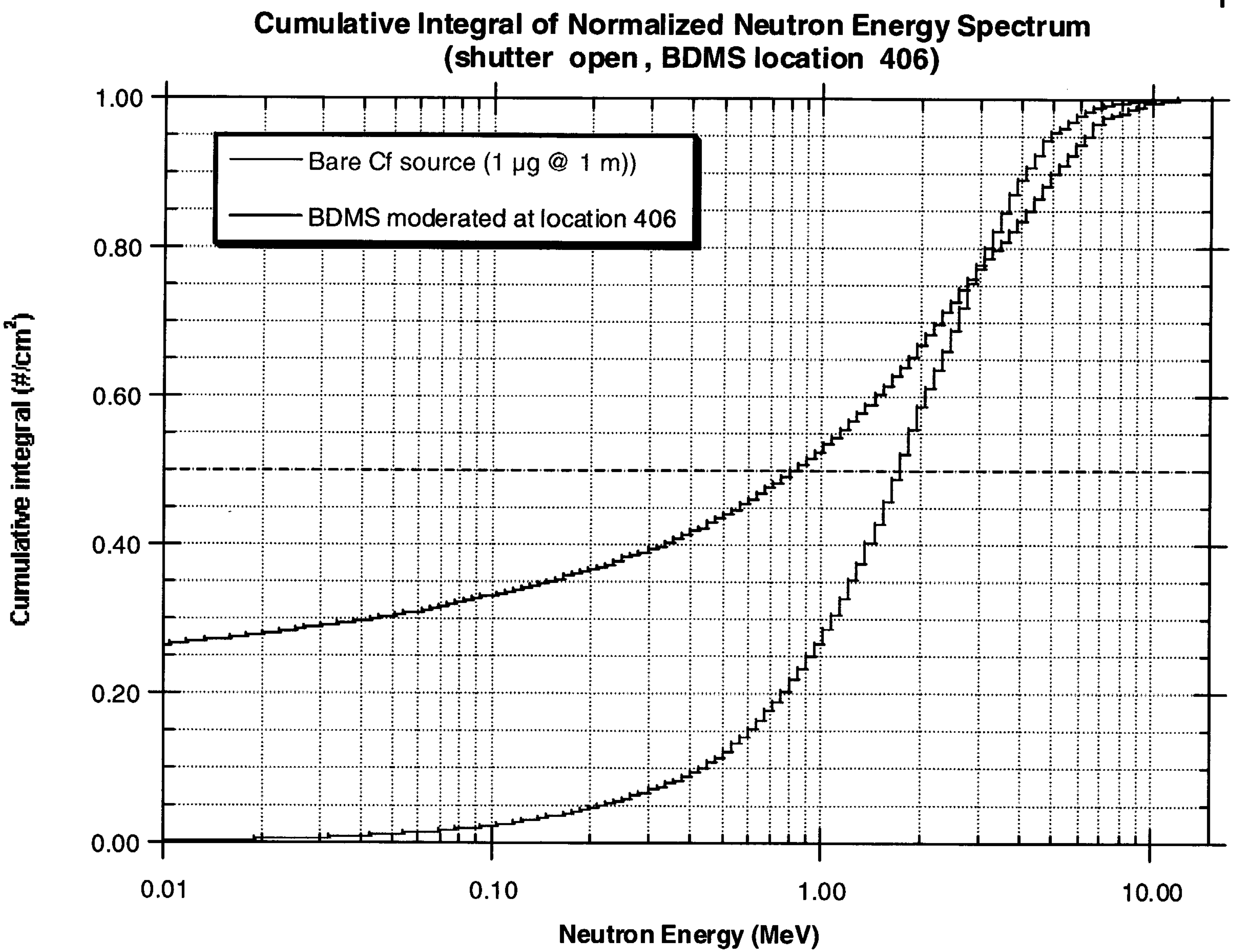
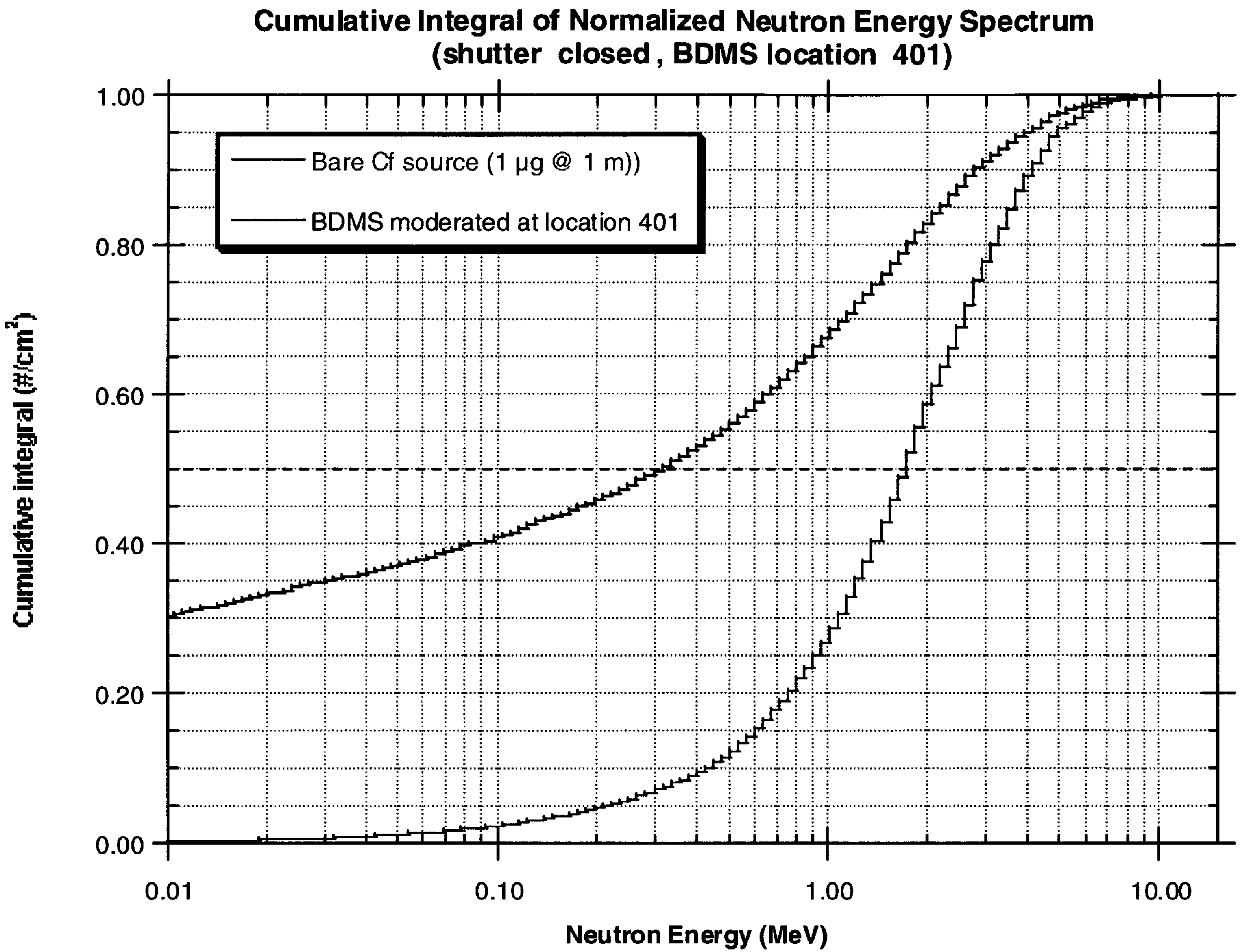

Cumulative Integral of Normalized Energy Spectrum
(shutter open , BDMS location 405)
Bare Cf source (1 µg @ 1 m))
BDMS moderated at location 405
Cumulative integral (#/cm^2)
1.00
0.80
0.60
0.40
0.20
0.00
0.01
0.10
1.00
10.00
Neutron Energy (MeV)

Figure 24



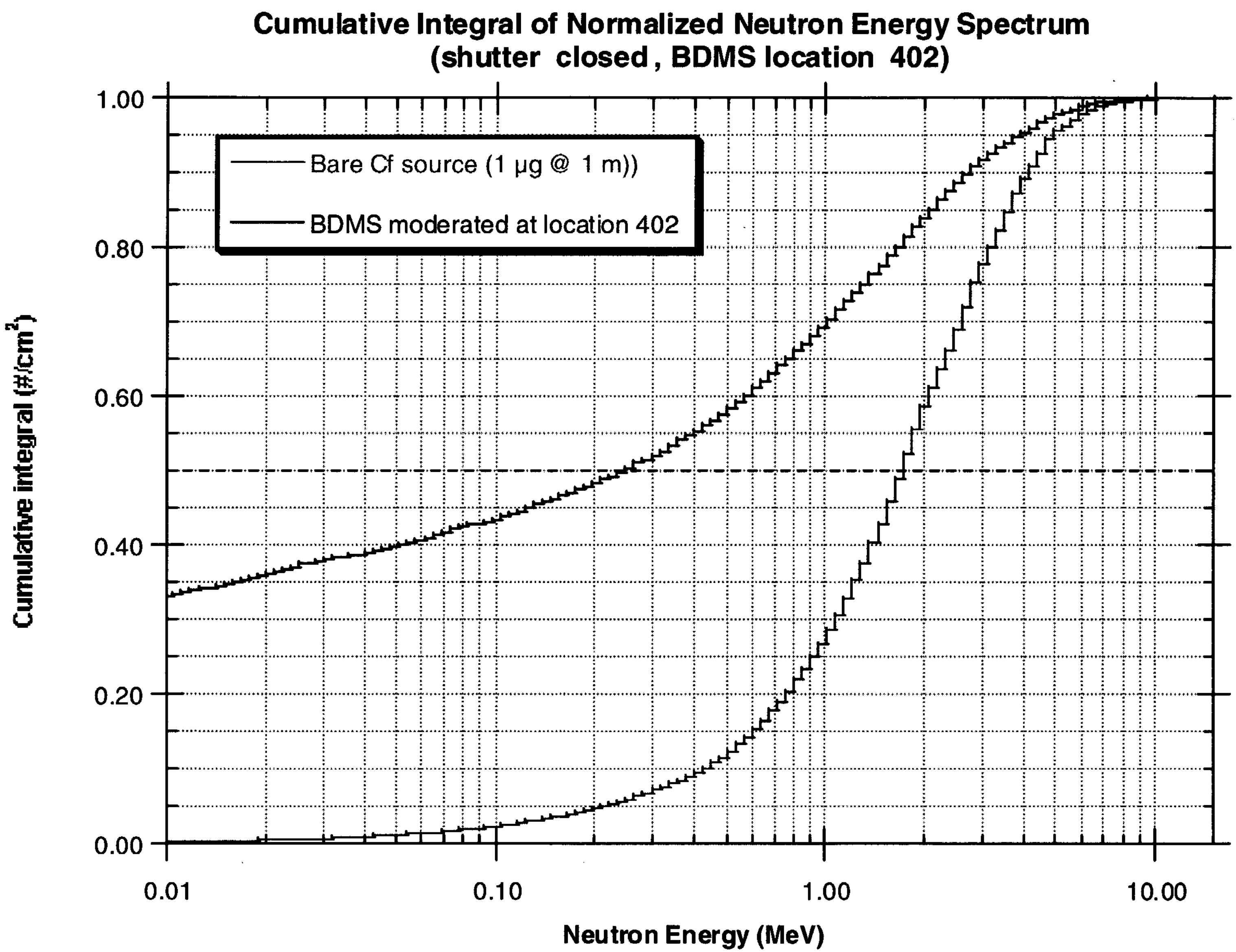
Cumulative Integral of Normalized Neutron Energy Spectrum
(shutter open, BDMS location 406)
Bare Cf source (1 µg @ 1 m))
BDMS moderated at location 406
Cumulative integral (#/cm2)
1.00
0.80
0.60
0.40
0.20
0.00
0.01
0.10
1.00
10.00
Neutron Energy (MeV)

Figure 25



Cumulative Integral of Normalized Neutron Energy Spectrum
(shutter closed, BDMS location 401)
Bare Cf source (1 μg @ 1 m))
BDMS moderated at location 401
Cumulative integral (#/cm^2)
1.00
0.80
0.60
0.40
0.20
0.00
0.01
0.10
1.00
10.00
Neutron Energy (MeV)

Figure 26



Cumulative Integral of Normalized Neutron Energy Spectrum
(shutter closed, BDMS location 402)
Bare Cf source (1 µg @ 1 m))
BDMS moderated at location 402
Cumulative integral (#/cm²)
1.00
0.80
0.60
0.40
0.20
0.00
0.01
0.10
1.00
10.00
Neutron Energy (MeV)

Figure 27

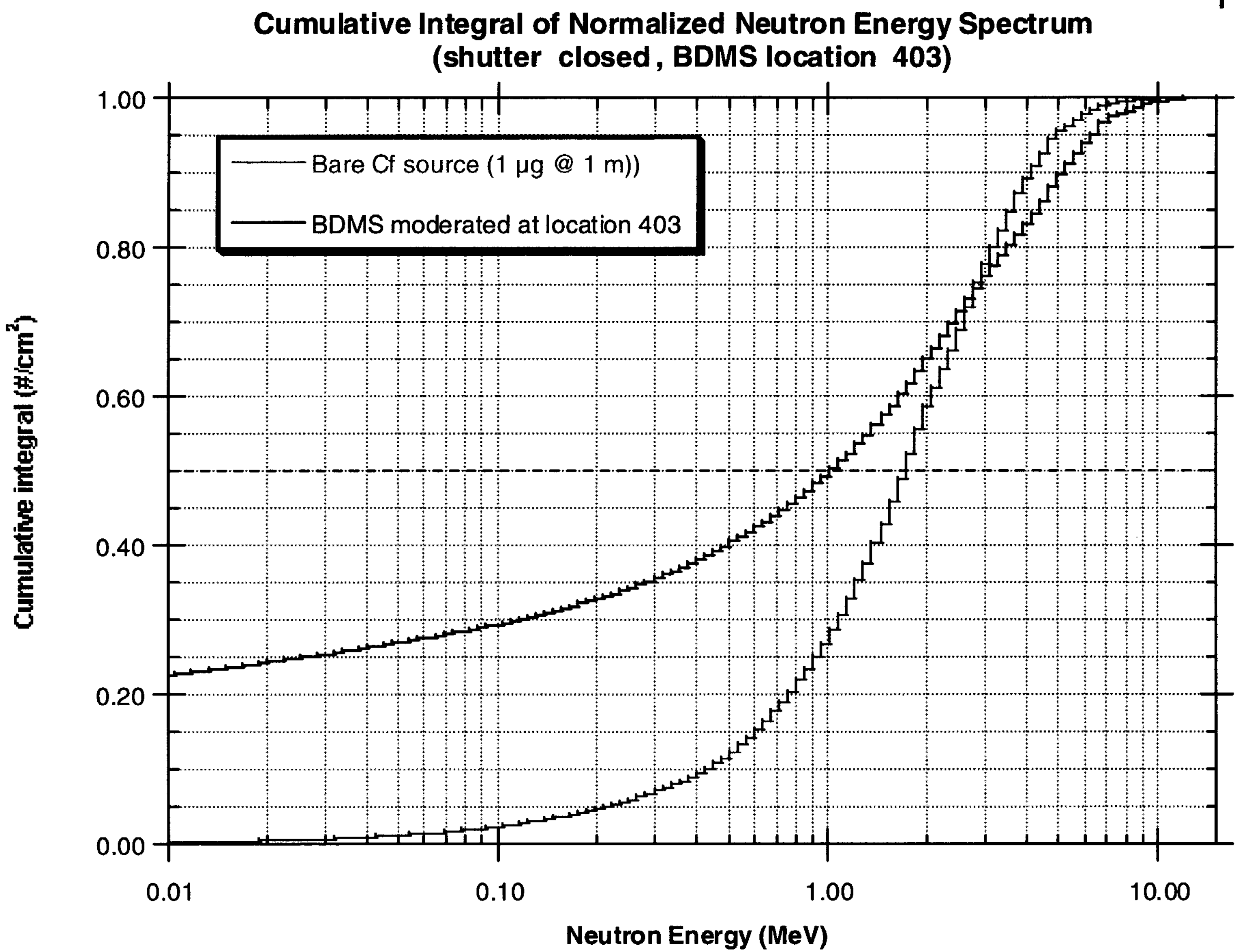
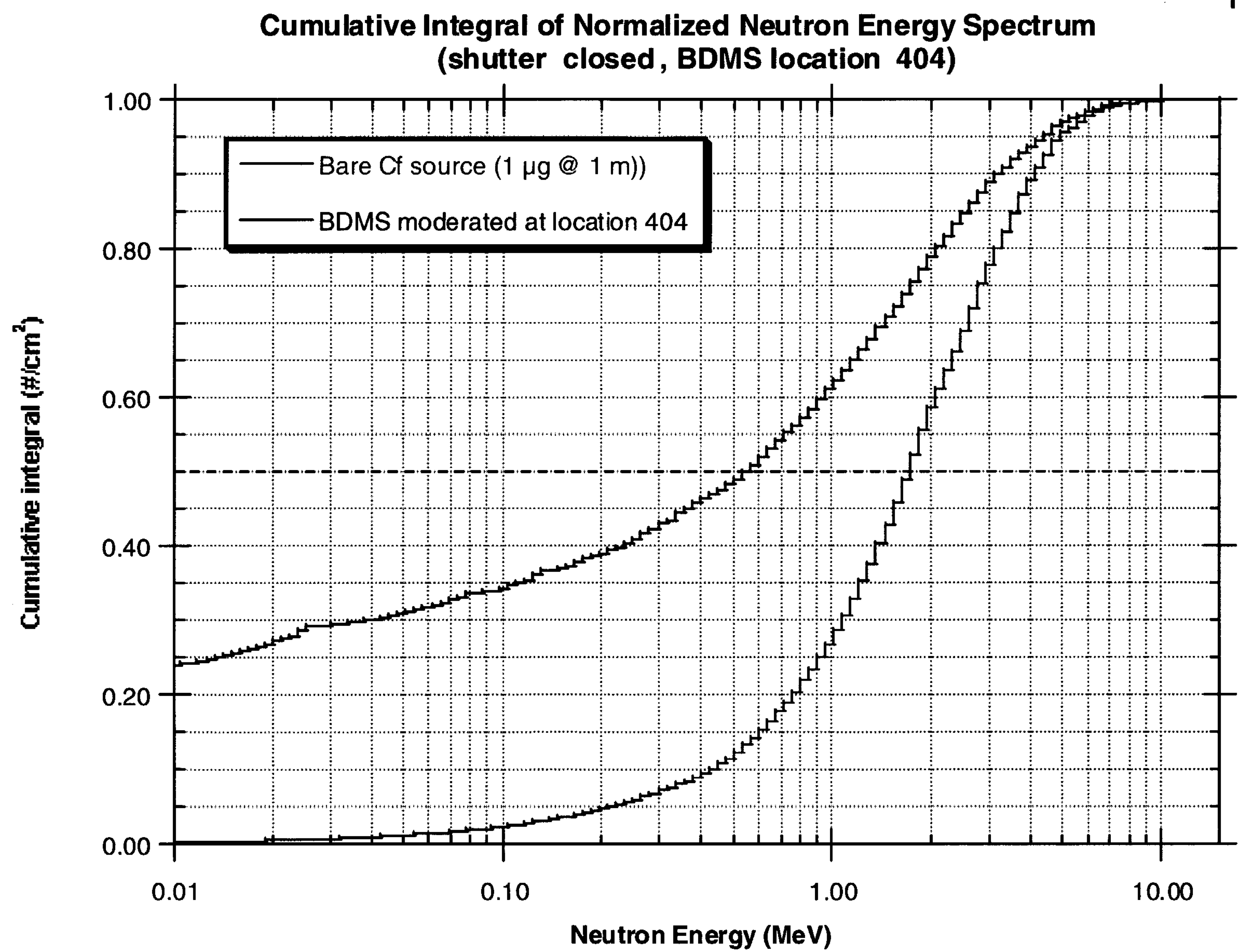

Cumulative Integral of Normalized Neutron Energy Spectrum
(shutter closed, BDMS location 403)
Bare Cf source (1 µg @ 1 m))
BDMS moderated at location 403
Cumulative integral (#/cm^2)
1.00
0.80
0.60
0.40
0.20
0.00
0.01
0.10
1.00
10.00
Neutron Energy (MeV)

Figure 28



Cumulative Integral of Normalized Neutron Energy Spectrum
(shutter closed, BDMS location 404)
Bare Cf source (1 µg @ 1 m))
BDMS moderated at location 404
1.00
0.80
0.60
0.40
0.20
0.00
Cumulative integral (#/cm^2)
0.01
0.10
1.00
10.00
Neutron Energy (MeV)

Figure 29

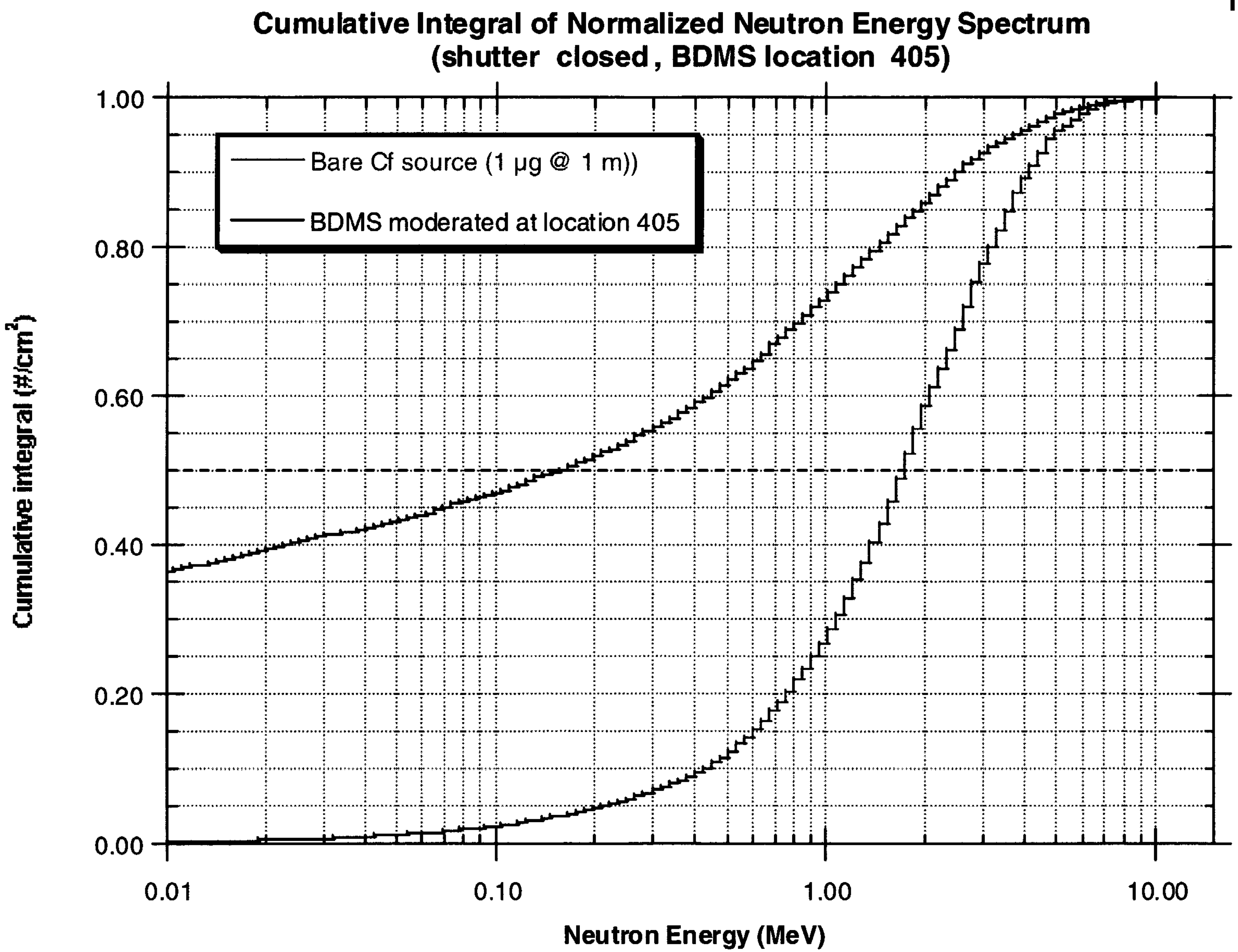
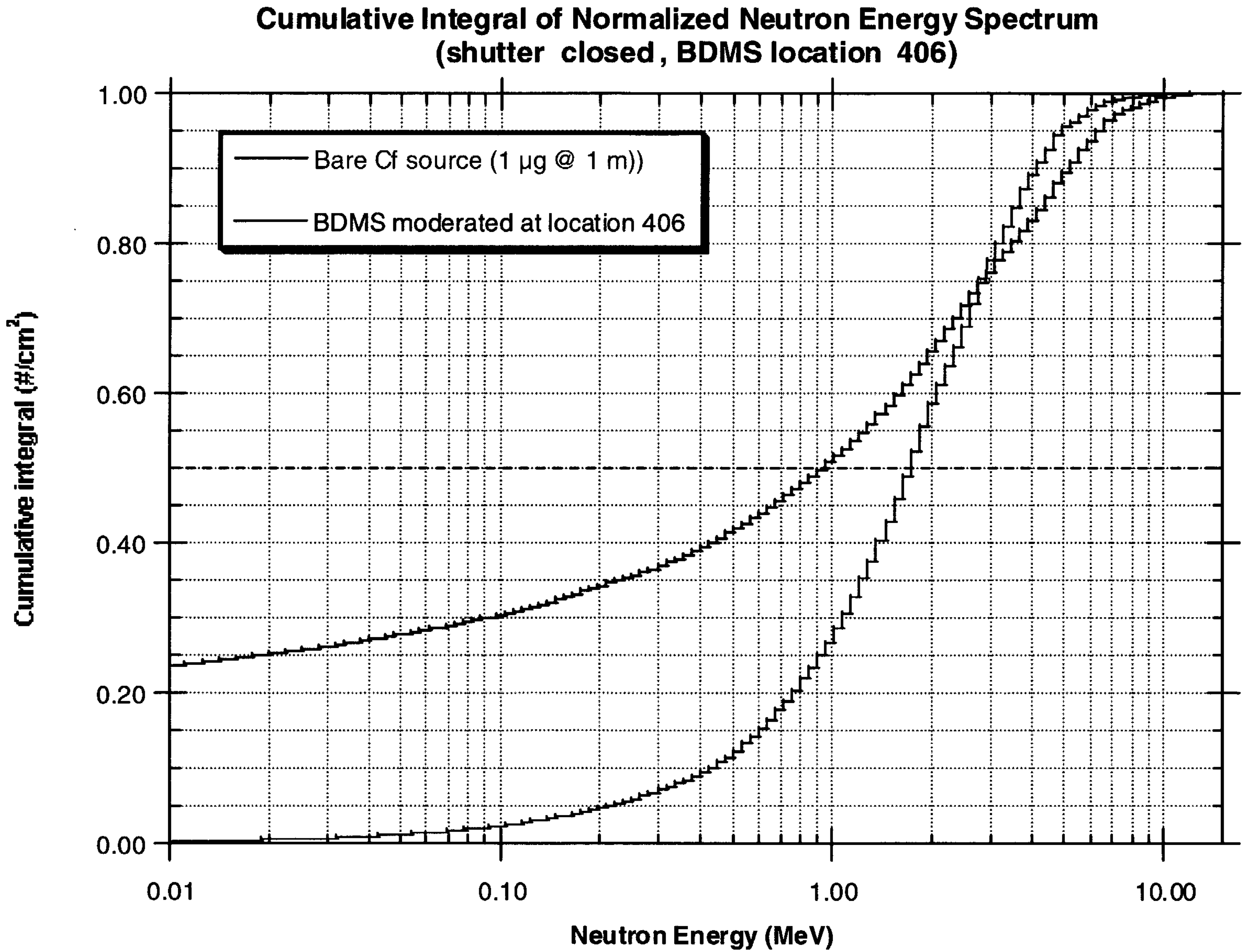
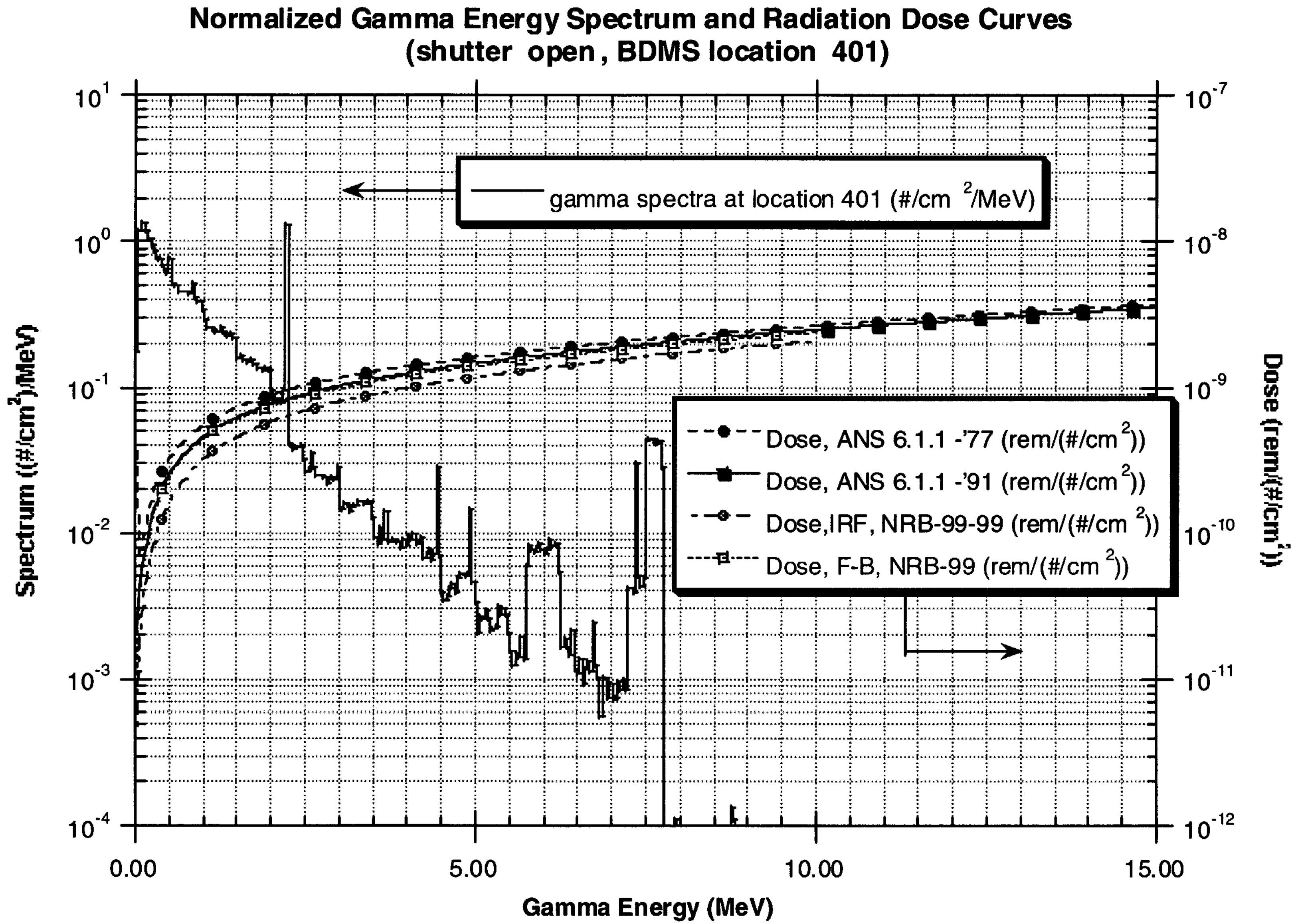

Cumulative Integral of Normalized Neutron Energy Spectrum
(shutter closed, BDMS location 405)
Bare Cf source (1 μg @ 1 m))
BDMS moderated at location 405
Cumulative integral (#/cm²)
1.00
0.80
0.60
0.40
0.20
0.00
0.01
0.10
1.00
10.00
Neutron Energy (MeV)

Figure 30



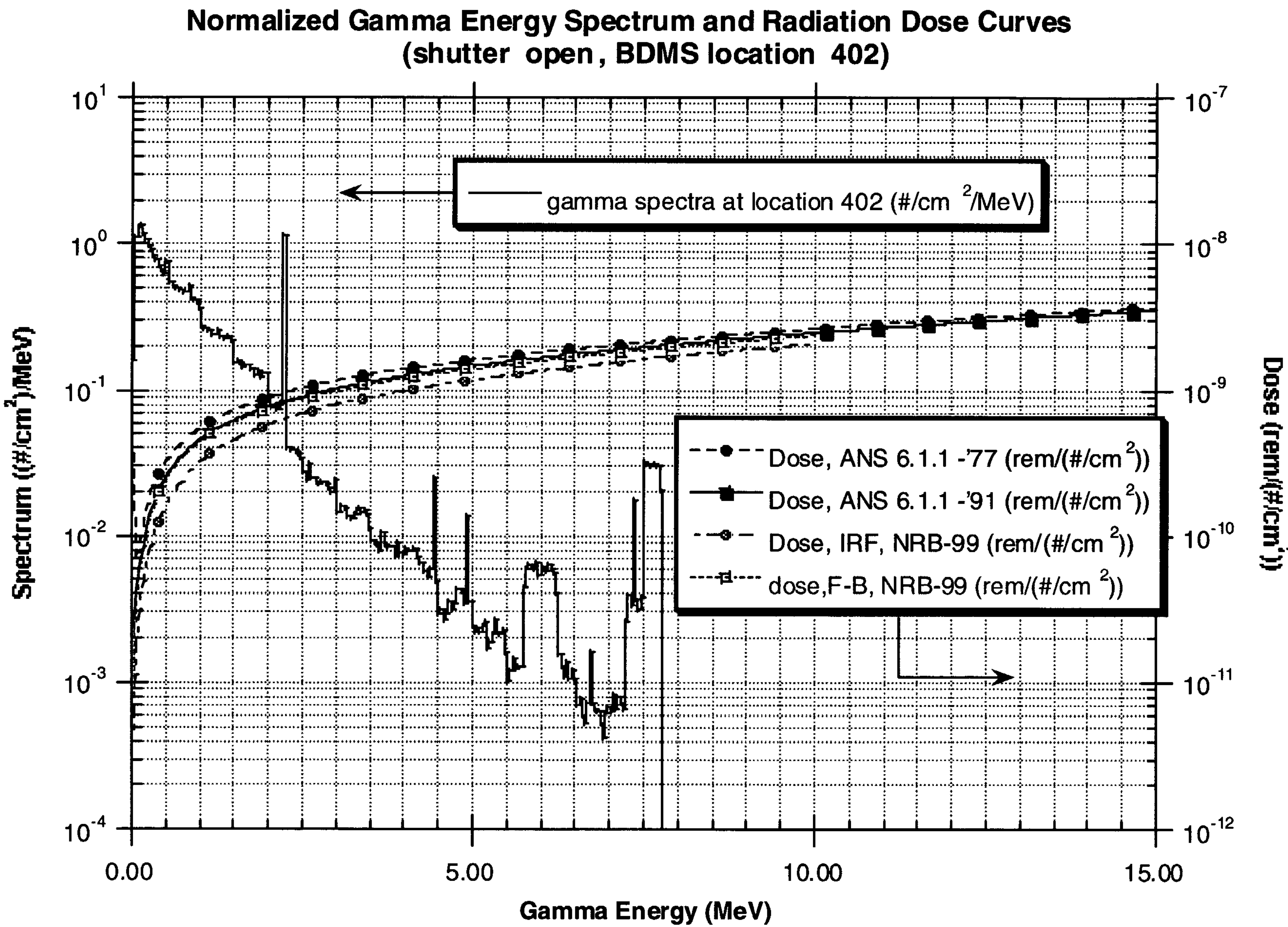
Cumulative Integral of Normalized Neutron Energy Spectrum
(shutter closed, BDMS location 406)
Bare Cf source (1 µg @ 1 m))
BDMS moderated at location 406
Cumulative integral (#/cm^2)
Neutron Energy (MeV)
1.00
0.80
0.60
0.40
0.20
0.00
0.01
0.10
1.00
10.00

Figure 31



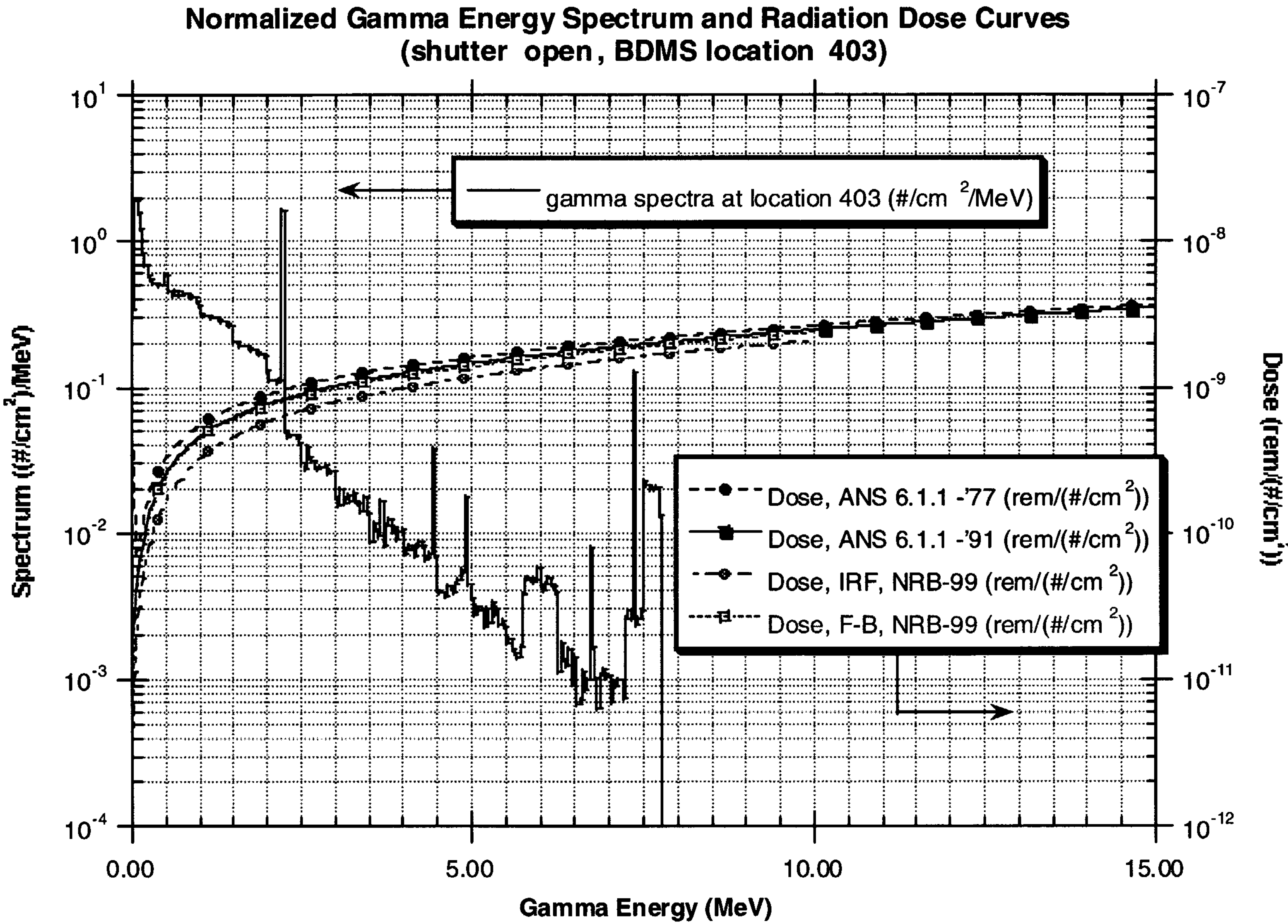
Normalized Gamma Energy Spectrum and Radiation Dose Curves
(shutter open, BDMS location 401)
gamma spectra at location 401 (#/cm 2/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm 2))
Dose, ANS 6.1.1 -'91 (rem/(#/cm 2))
Dose,IRF, NRB-99-99 (rem/(#/cm 2))
Dose, F-B, NRB-99 (rem/(#/cm 2))
Spectrum ((#/cm2)/MeV)
Dose (rem/(#/cm2))
Gamma Energy (MeV)
0.00
5.00
10.00
15.00
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12

Figure 32



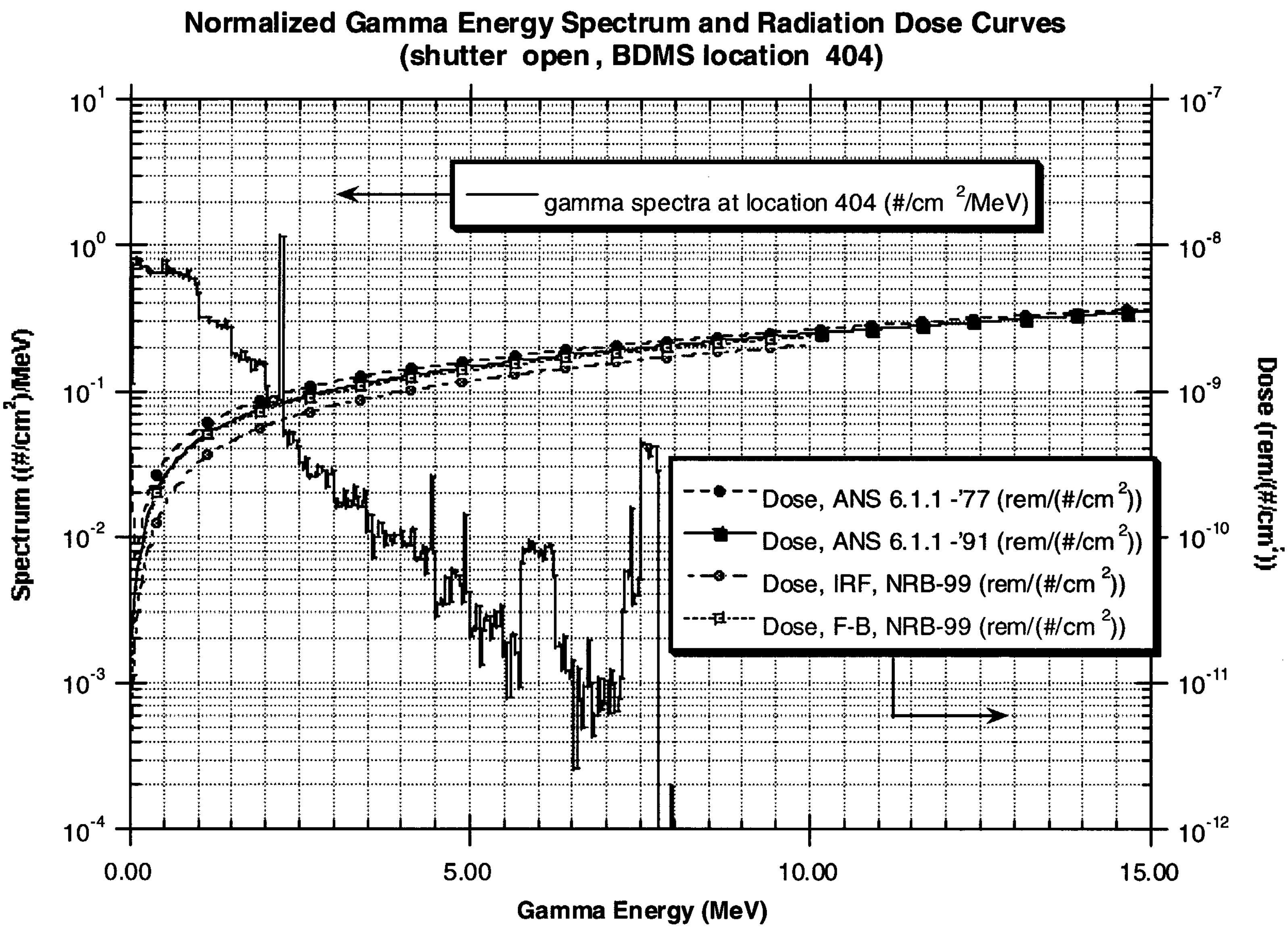
Normalized Gamma Energy Spectrum and Radiation Dose Curves
(shutter open, BDMS location 402)
gamma spectra at location 402 (#/cm 2/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm 2))
Dose, ANS 6.1.1 -'91 (rem/(#/cm 2))
Dose, IRF, NRB-99 (rem/(#/cm 2))
dose,F-B, NRB-99 (rem/(#/cm 2))
Spectrum ((#/cm2)/MeV)
Dose (rem/(#/cm2))
Gamma Energy (MeV)
0.00
5.00
10.00
15.00
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12

Figure 33



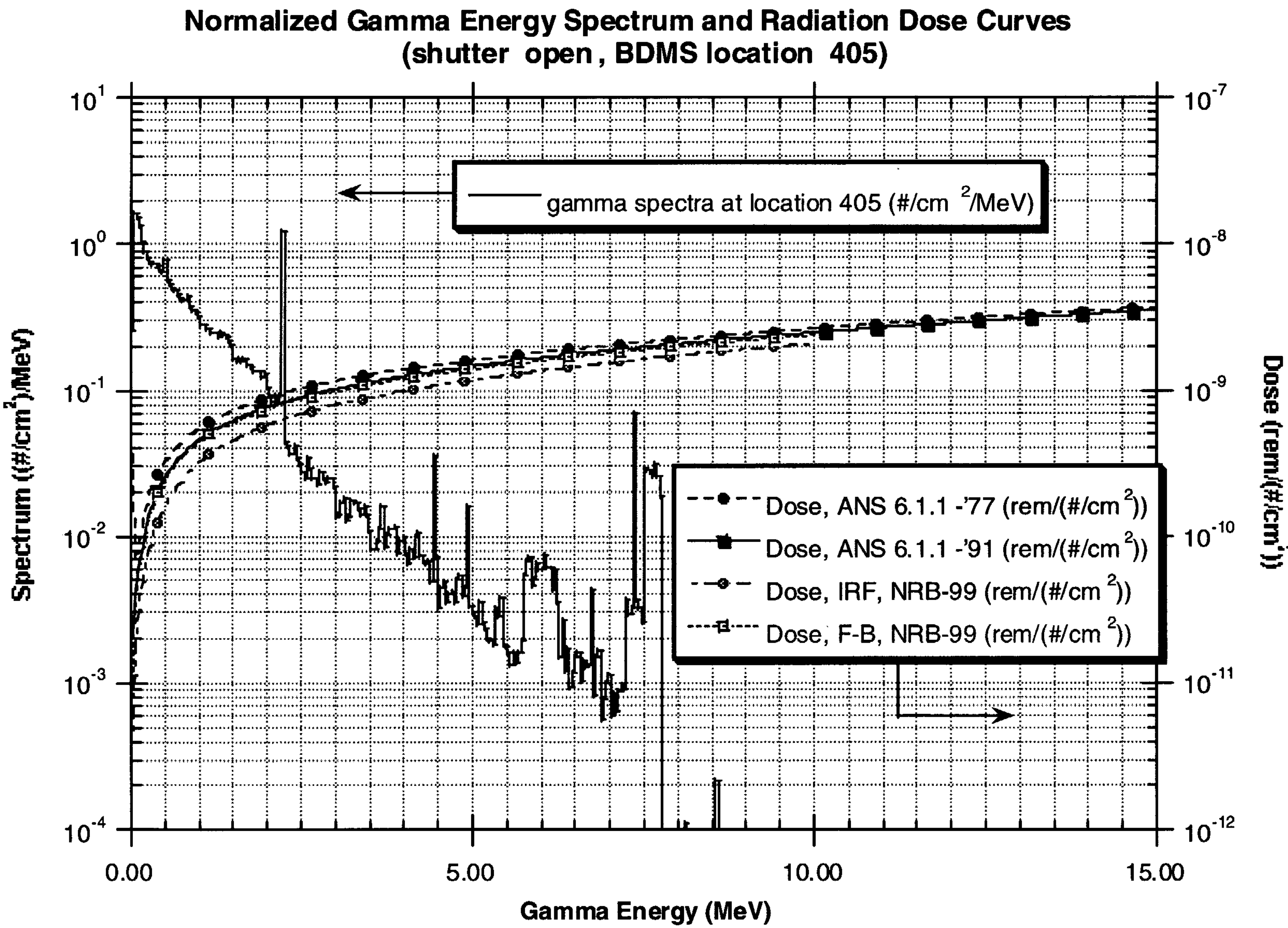
Normalized Gamma Energy Spectrum and Radiation Dose Curves
(shutter open, BDMS location 403)
gamma spectra at location 403 (#/cm 2/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm 2))
Dose, ANS 6.1.1 -'91 (rem/(#/cm 2))
Dose, IRF, NRB-99 (rem/(#/cm 2))
Dose, F-B, NRB-99 (rem/(#/cm 2))
Spectrum ((#/cm 2)/MeV)
Dose (rem/(#/cm 2))
Gamma Energy (MeV)
0.00
5.00
10.00
15.00
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12

Figure 34



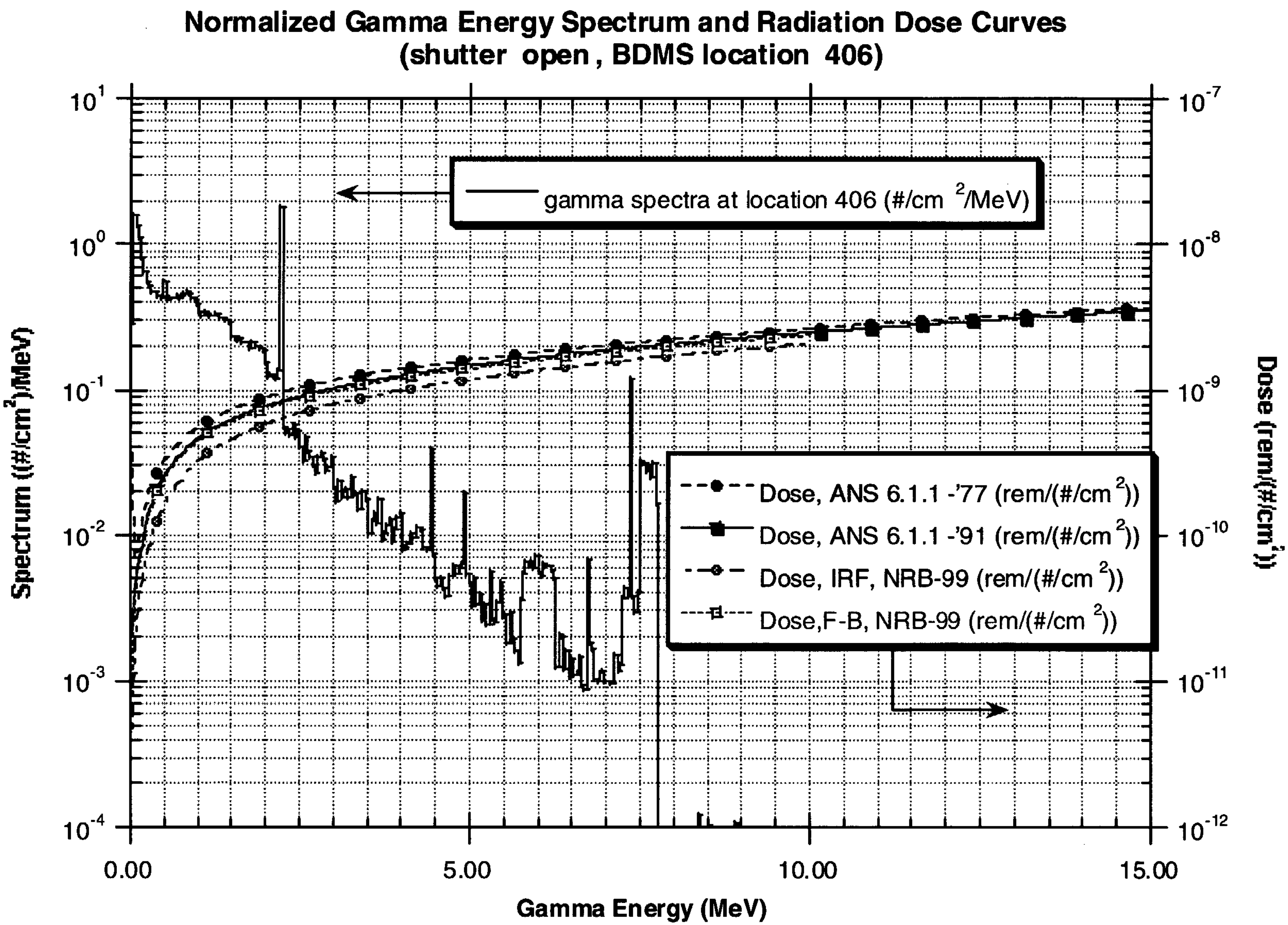
Normalized Gamma Energy Spectrum and Radiation Dose Curves
(shutter open, BDMS location 404)
gamma spectra at location 404 (#/cm 2/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm 2))
Dose, ANS 6.1.1 -'91 (rem/(#/cm 2))
Dose, IRF, NRB-99 (rem/(#/cm 2))
Dose, F-B, NRB-99 (rem/(#/cm 2))
Spectrum ((#/cm2)/MeV)
Dose (rem/(#/cm2))
Gamma Energy (MeV)
0.00
5.00
10.00
15.00
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}

Figure 35



Normalized Gamma Energy Spectrum and Radiation Dose Curves
(shutter open, BDMS location 405)
gamma spectra at location 405 (#/cm 2/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm 2))
Dose, ANS 6.1.1 -'91 (rem/(#/cm 2))
Dose, IRF, NRB-99 (rem/(#/cm 2))
Dose, F-B, NRB-99 (rem/(#/cm 2))
Spectrum ((#/cm 2)/MeV)
Dose (rem/(#/cm 2))
Gamma Energy (MeV)
0.00
5.00
10.00
15.00
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12

Figure 36



Normalized Gamma Energy Spectrum and Radiation Dose Curves
(shutter open , BDMS location 406)
gamma spectra at location 406 (#/cm 2/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm 2))
Dose, ANS 6.1.1 -'91 (rem/(#/cm 2))
Dose, IRF, NRB-99 (rem/(#/cm 2))
Dose,F-B, NRB-99 (rem/(#/cm 2))
Spectrum ((#/cm2)/MeV)
Dose (rem/(#/cm2))
Gamma Energy (MeV)
0.00
5.00
10.00
15.00

Figure 37

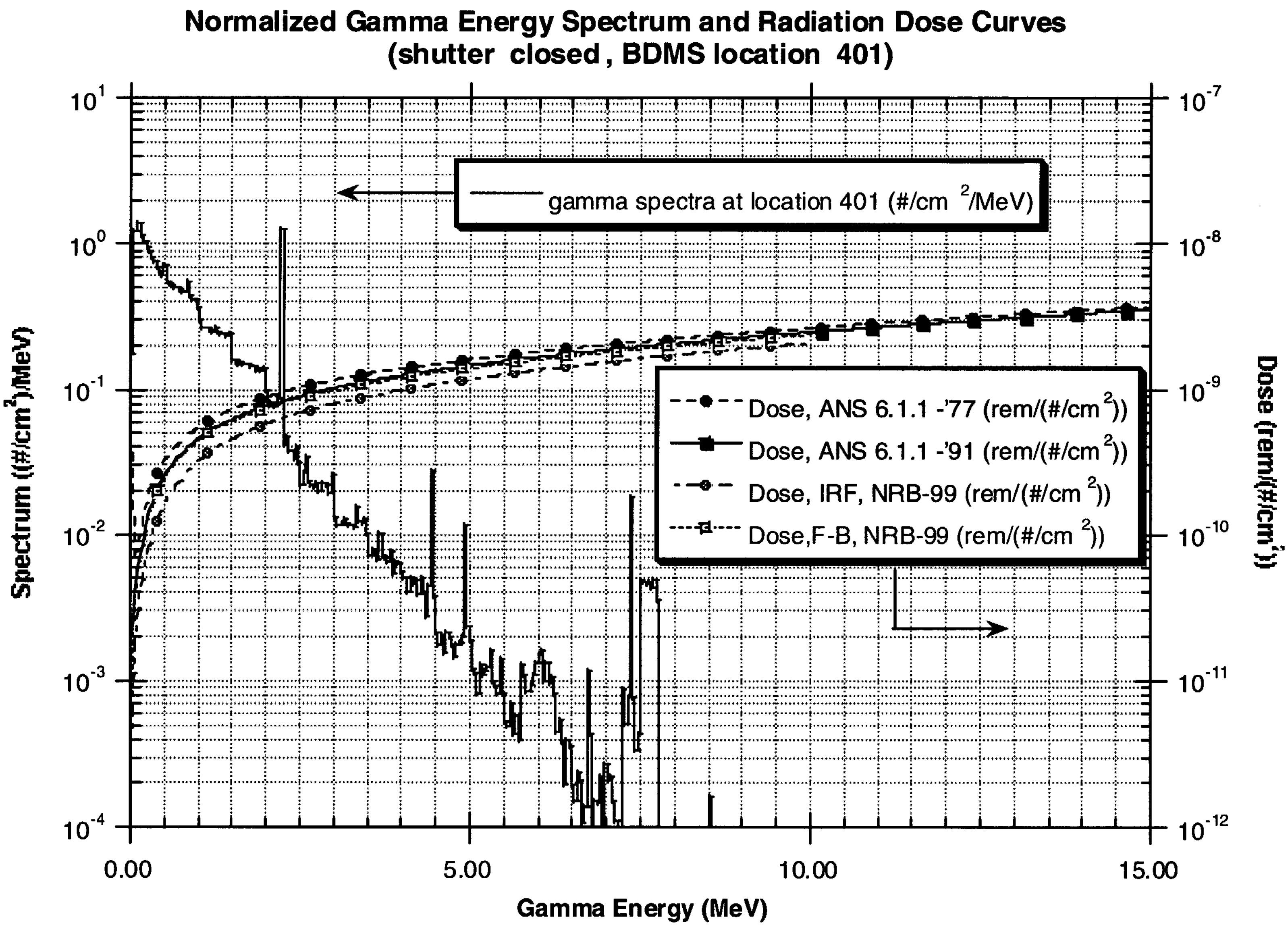
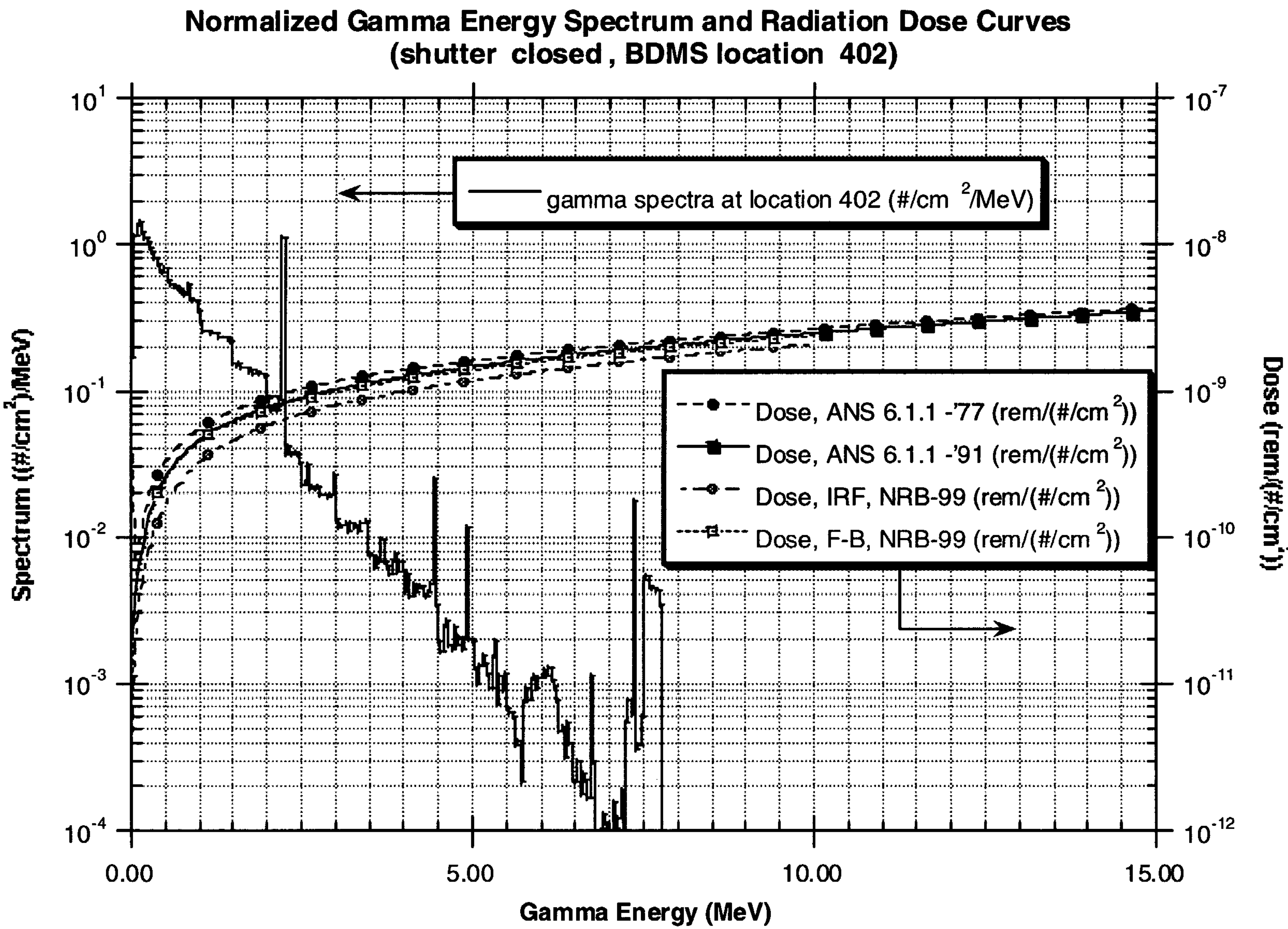
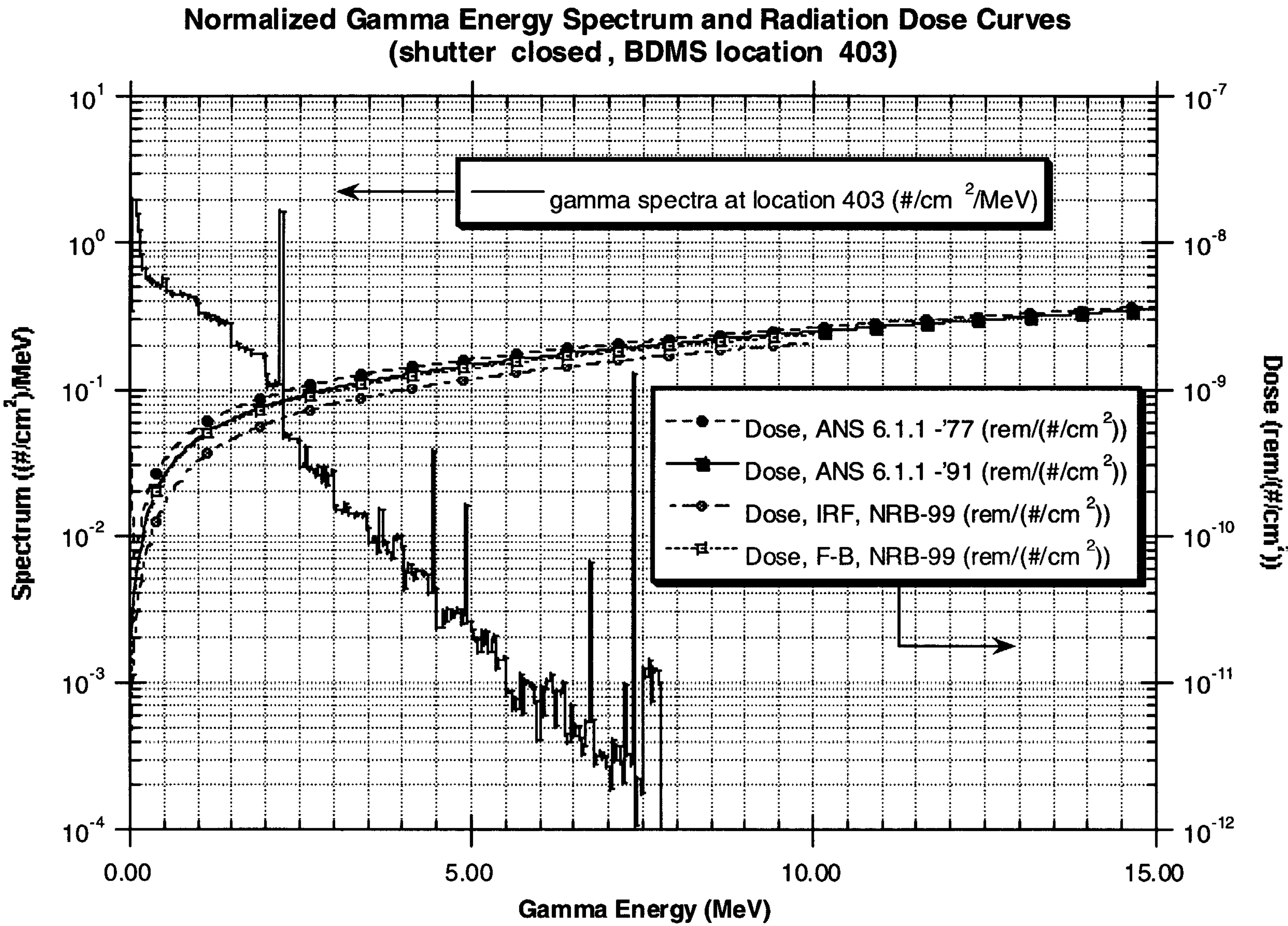

Normalized Gamma Energy Spectrum and Radiation Dose Curves
(shutter closed , BDMS location 401)
gamma spectra at location 401 (#/cm 2/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm 2))
Dose, ANS 6.1.1 -'91 (rem/(#/cm 2))
Dose, IRF, NRB-99 (rem/(#/cm 2))
Dose,F-B, NRB-99 (rem/(#/cm 2))
Spectrum ((#/cm 2)/MeV)
Dose (rem/(#/cm 2))
Gamma Energy (MeV)
0.00
5.00
10.00
15.00
10 1
10 0
10 -1
10 -2
10 -3
10 -4
10 -7
10 -8
10 -9
10 -10
10 -11
10 -12

Figure 38



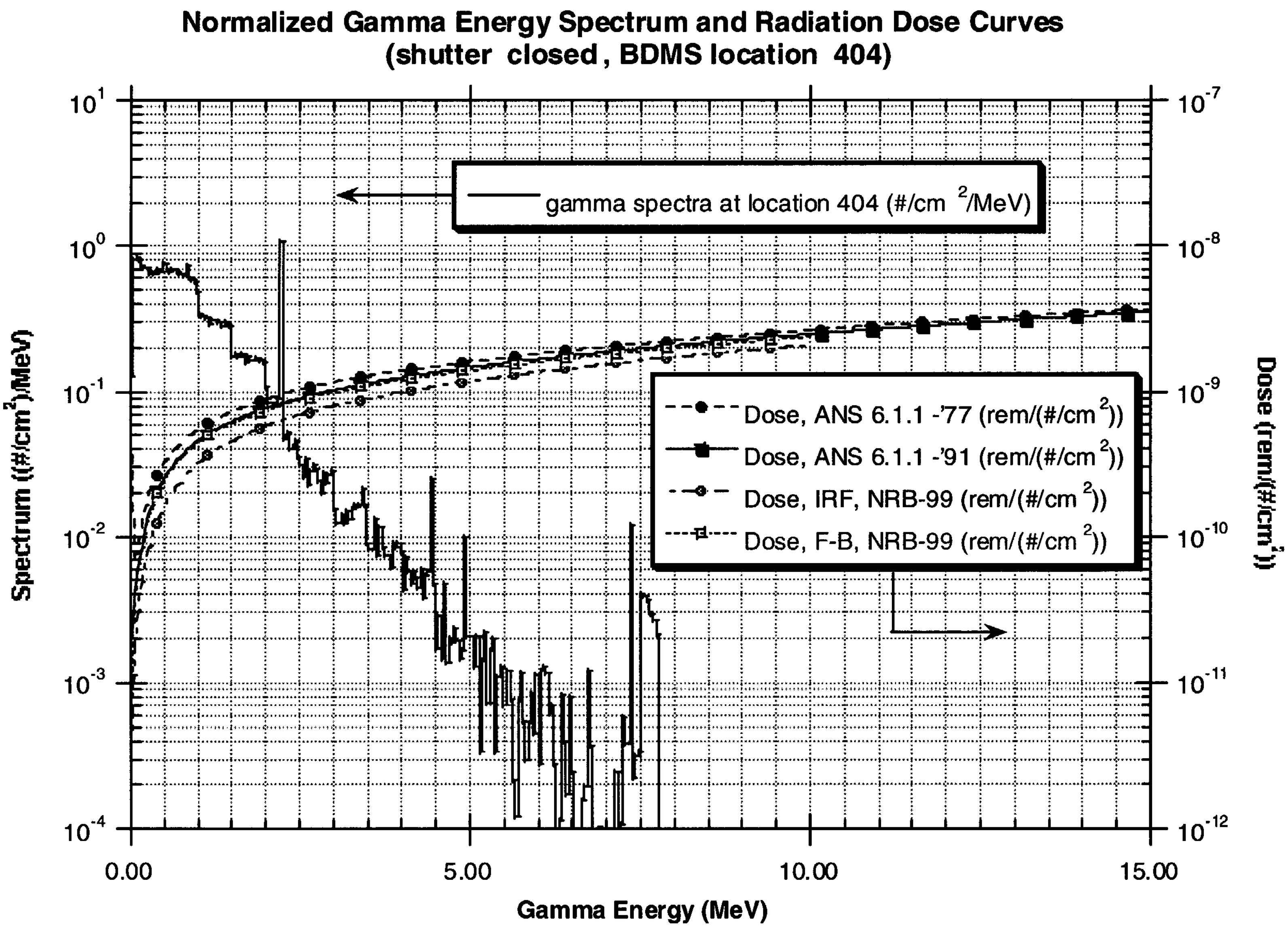
Normalized Gamma Energy Spectrum and Radiation Dose Curves
(shutter closed , BDMS location 402)
gamma spectra at location 402 (#/cm 2/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm 2))
Dose, ANS 6.1.1 -'91 (rem/(#/cm 2))
Dose, IRF, NRB-99 (rem/(#/cm 2))
Dose, F-B, NRB-99 (rem/(#/cm 2))
Spectrum ((#/cm2)/MeV)
Dose (rem/(#/cm2))
Gamma Energy (MeV)
0.00
5.00
10.00
15.00
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12

Figure 39



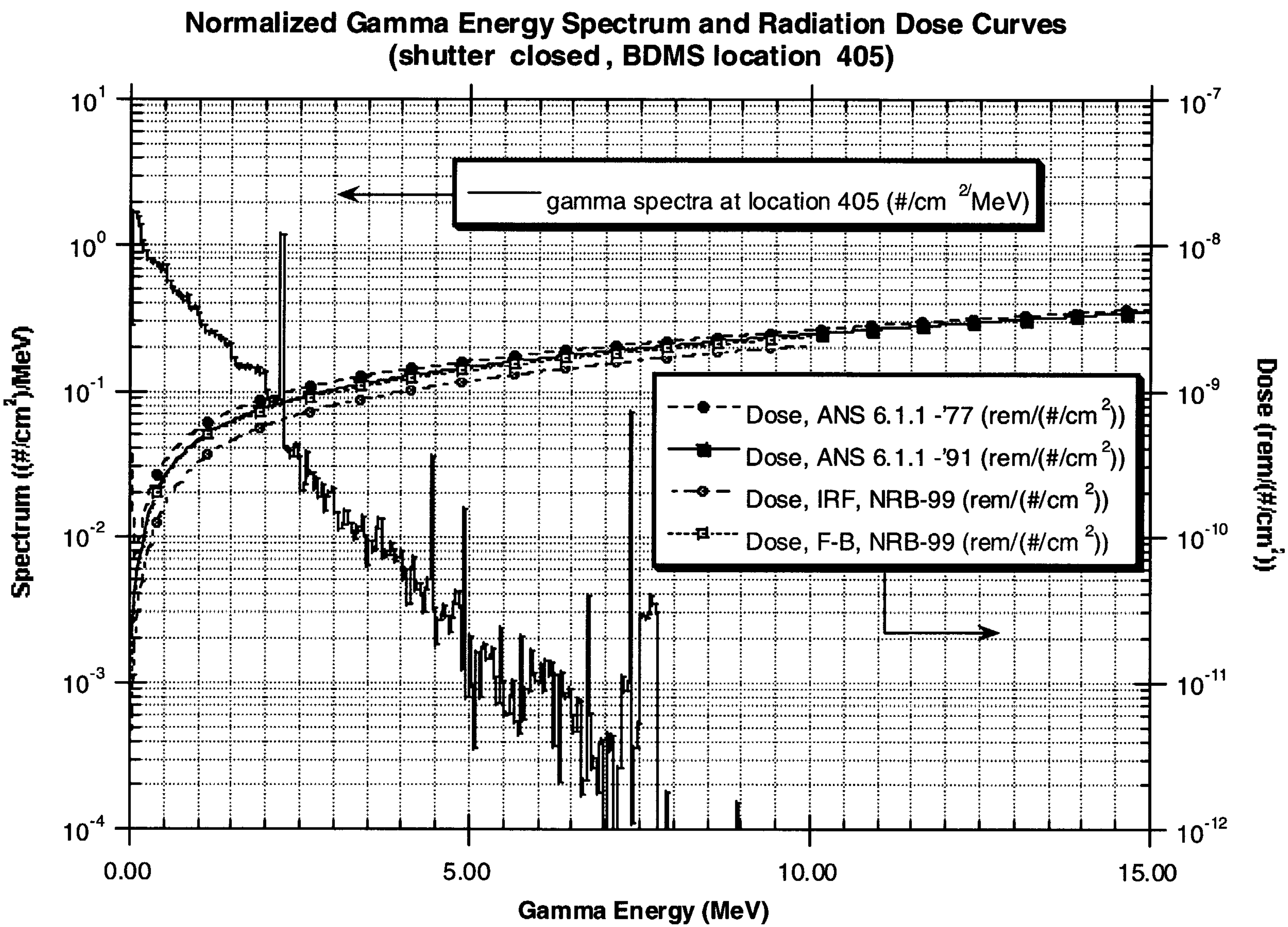
Normalized Gamma Energy Spectrum and Radiation Dose Curves
(shutter closed, BDMS location 403)
gamma spectra at location 403 (#/cm 2/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm 2))
Dose, ANS 6.1.1 -'91 (rem/(#/cm 2))
Dose, IRF, NRB-99 (rem/(#/cm 2))
Dose, F-B, NRB-99 (rem/(#/cm 2))
Spectrum ((#/cm2)/MeV)
Dose (rem/(#/cm2))
Gamma Energy (MeV)
0.00
5.00
10.00
15.00
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12

Figure 40



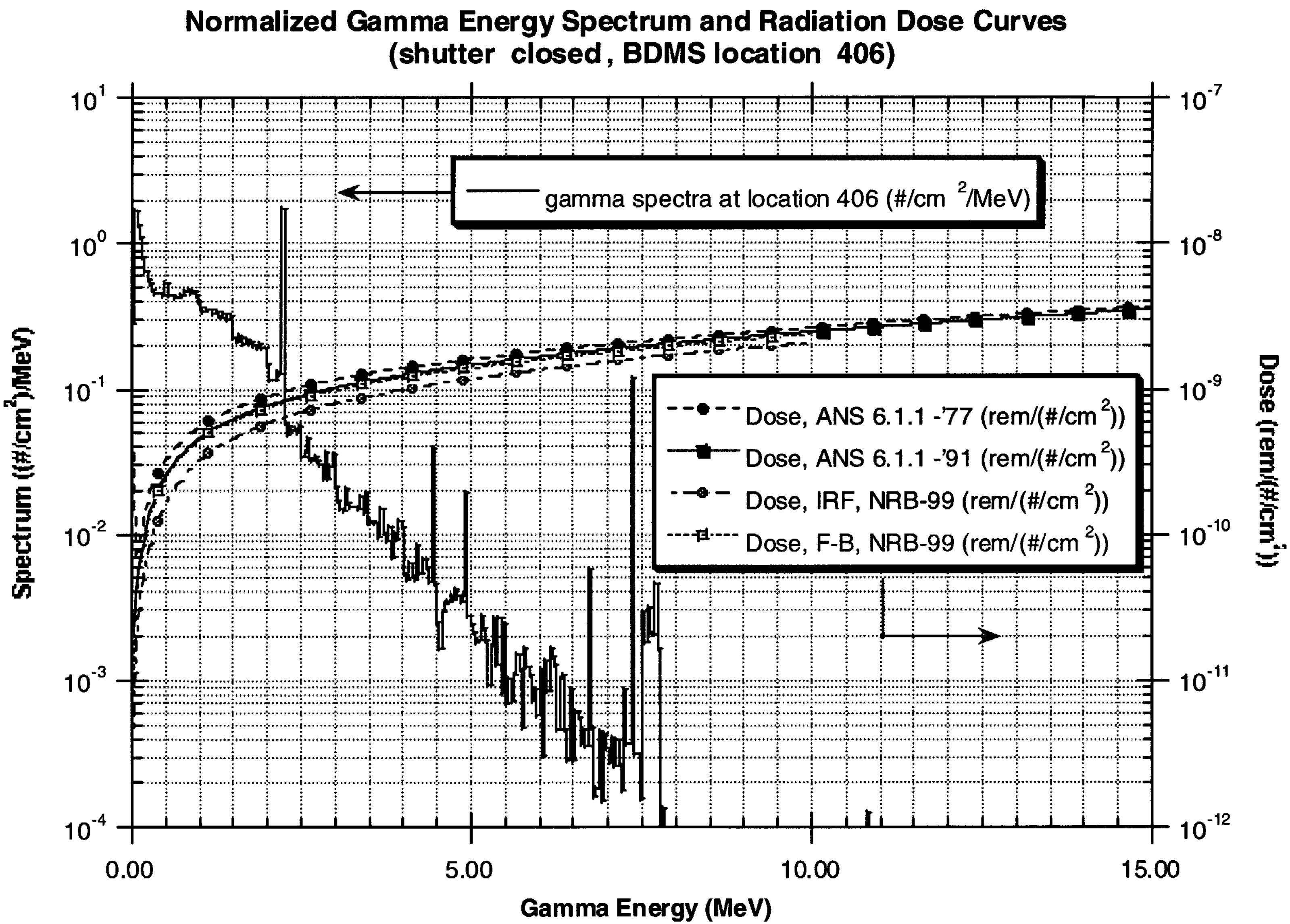
Normalized Gamma Energy Spectrum and Radiation Dose Curves
(shutter closed, BDMS location 404)
gamma spectra at location 404 (#/cm ²/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm²))
Dose, ANS 6.1.1 -'91 (rem/(#/cm²))
Dose, IRF, NRB-99 (rem/(#/cm²))
Dose, F-B, NRB-99 (rem/(#/cm²))
Spectrum ((#/cm²)/MeV)
Dose (rem/(#/cm²))
Gamma Energy (MeV)
0.00
5.00
10.00
15.00
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²

Figure 41



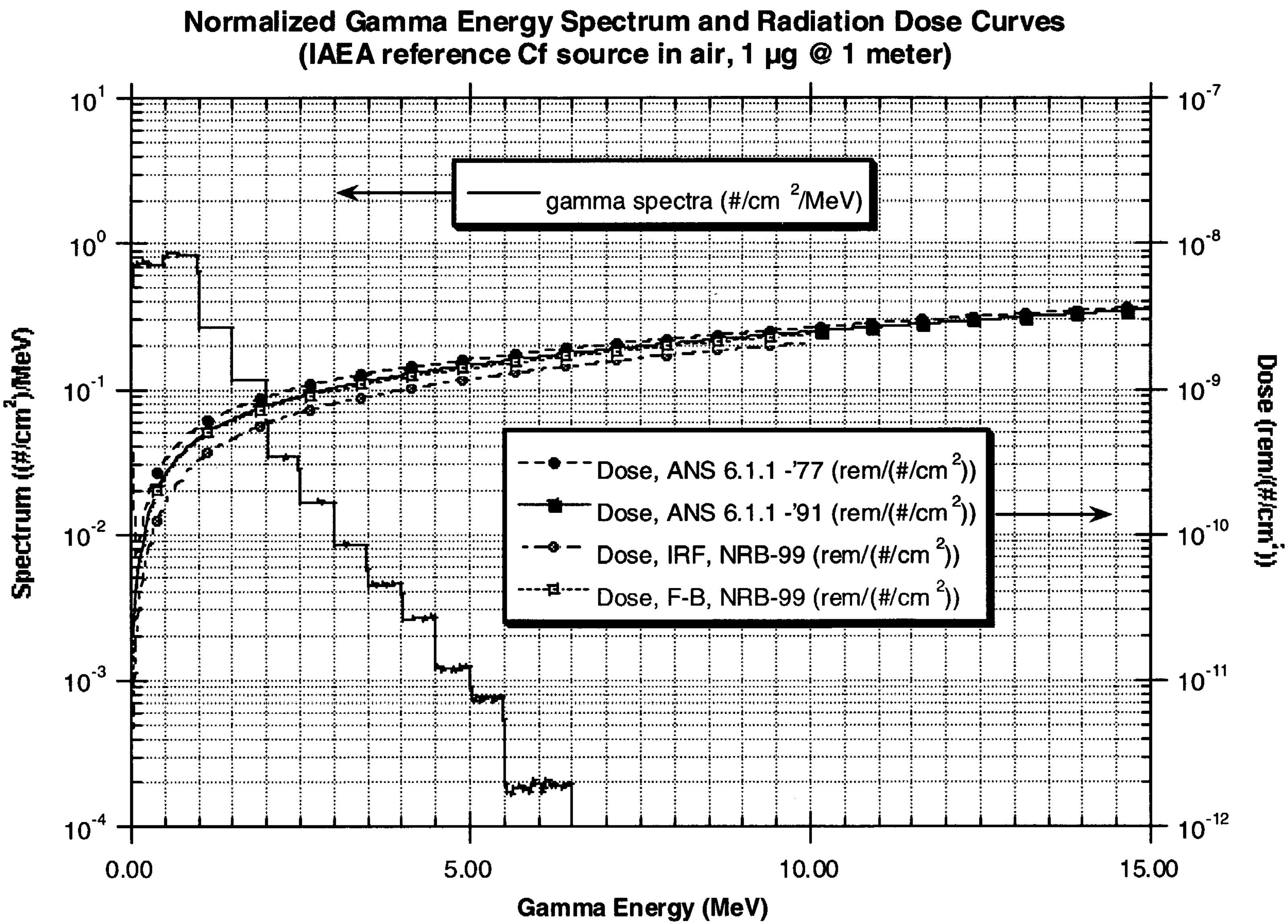
Normalized Gamma Energy Spectrum and Radiation Dose Curves
(shutter closed, BDMS location 405)
gamma spectra at location 405 (#/cm 2/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm 2))
Dose, ANS 6.1.1 -'91 (rem/(#/cm 2))
Dose, IRF, NRB-99 (rem/(#/cm 2))
Dose, F-B, NRB-99 (rem/(#/cm 2))
Spectrum ((#/cm2)/MeV)
Dose (rem/(#/cm2))
Gamma Energy (MeV)
0.00
5.00
10.00
15.00
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12

Figure 42



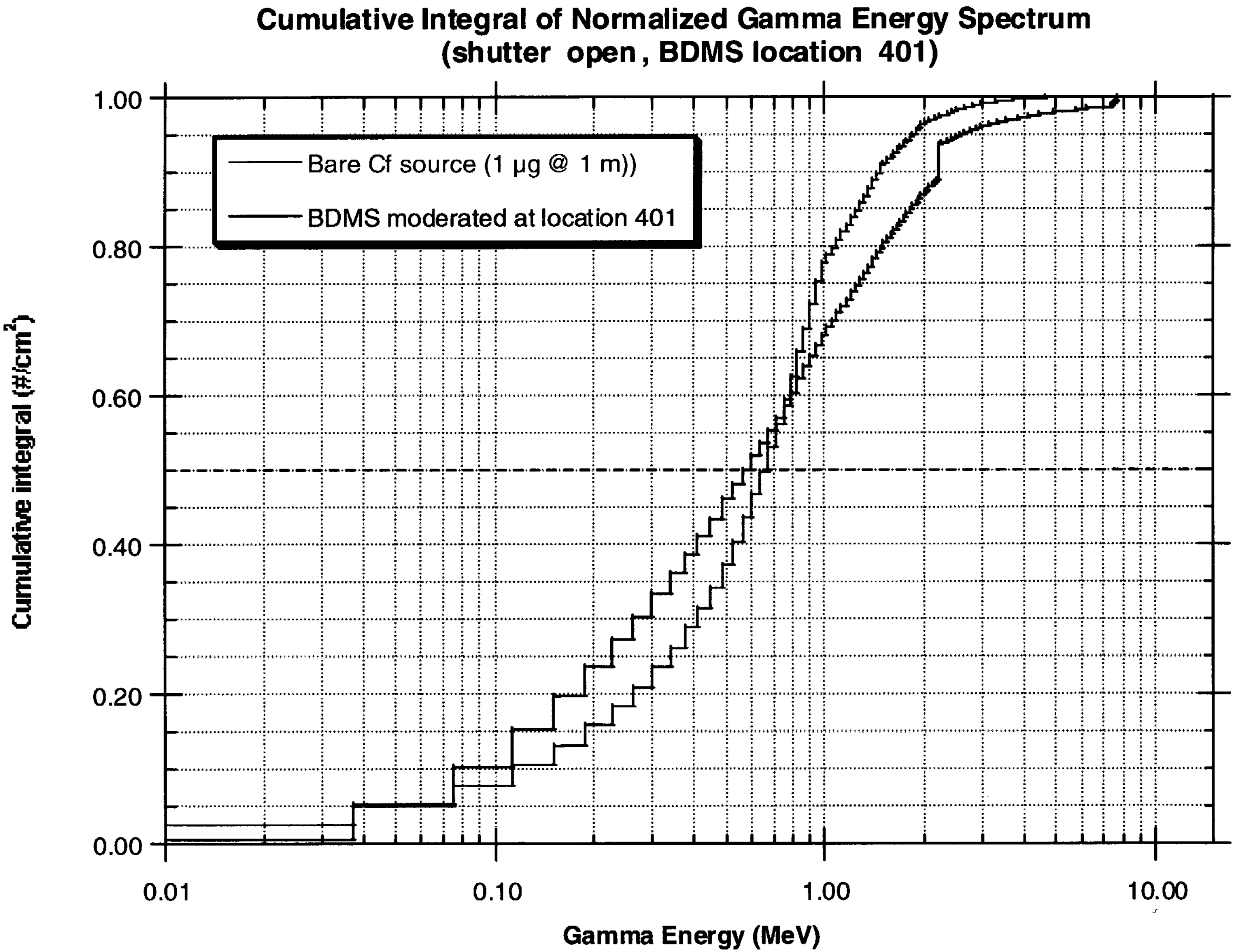
Normalized Gamma Energy Spectrum and Radiation Dose Curves
(shutter closed, BDMS location 406)
gamma spectra at location 406 (#/cm 2/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm 2))
Dose, ANS 6.1.1 -'91 (rem/(#/cm 2))
Dose, IRF, NRB-99 (rem/(#/cm 2))
Dose, F-B, NRB-99 (rem/(#/cm 2))
Spectrum ((#/cm2)/MeV)
Dose (rem/(#/cm2))
Gamma Energy (MeV)
0.00
5.00
10.00
15.00
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12

Figure 43



Normalized Gamma Energy Spectrum and Radiation Dose Curves
(IAEA reference Cf source in air, 1 µg @ 1 meter)
gamma spectra (#/cm ²/MeV)
Dose, ANS 6.1.1 -'77 (rem/(#/cm ²))
Dose, ANS 6.1.1 -'91 (rem/(#/cm ²))
Dose, IRF, NRB-99 (rem/(#/cm ²))
Dose, F-B, NRB-99 (rem/(#/cm ²))
Spectrum ((#/cm²)/MeV)
Dose (rem/(#/cm²))
Gamma Energy (MeV)
0.00
5.00
10.00
15.00
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²

Figure 44


Cumulative Integral of Normalized Gamma Energy Spectrum
(shutter open, BDMS location 401)
Bare Cf source (1 µg @ 1 m))
BDMS moderated at location 401
Cumulative integral (#/cm²)
1.00
0.80
0.60
0.40
0.20
0.00
0.01
0.10
1.00
10.00
Gamma Energy (MeV)